

Action-Inspired Approach to Design of Navigation Techniques for Effective Spatial Learning in 3-D Virtual Environments

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Abstract

Navigation in large spaces is essential in any environment (both the real world and the virtual world) because one of the human fundamental needs is to know the surrounding environment and to freely navigate within the environment. For successful navigation in large-scale virtual environments (VEs), accurate spatial knowledge is required, especially in training and learning application domains. By acquiring accurate spatial knowledge, people can effectively understand spatial layout and objects in environments. In addition, spatial knowledge acquired from a large-scale VE can effectively be transferred to the real world activities.

Numerous navigation techniques have been proposed to support successful navigation and effective spatial knowledge acquisition in large-scale VEs. Among them, walking-like navigation techniques have been shown to support spatial knowledge acquisition more effectively in large-scale VEs, compared to non-body-based and non-walking-based navigation techniques. However, walking-like navigation techniques in large-scale VEs still have some issues, such as whole-body fatigue, large-controlled-space and specialized system configuration that make the walking-like navigation techniques less convenient, and consequently less commonly used. Due to these issues, convenient non-walking-like navigation techniques are preferred although they are less effective for spatial learning. While most research and development efforts are centered around walking-like navigation techniques, a fresh approach is needed to effectively and conveniently support for human spatial learning.

We propose an *action-inspired approach*, to design convenient and effective navigation techniques for supporting people to acquire accurate spatial knowledge acquisition or improve spatial learning. The *action-inspired approach* is based on our insights from learning, neuropsychological and neurophysiological theories. The theories suggest that *action* and *perception* are closely related and core elements of learning. Our observations indicated that specific body-parts are not necessarily related to learning.

We identified two types of action-inspired approach, body-turn based and action-transferred. Body-turn based approach keeps body-turn but replaces cyclic leg-movements of original walking action

with more convenient control to resolve the issues presented from walking-like navigation techniques. Action-transferred approach addresses the design trade-offs between effectiveness and convenience, the core concept of which is grounded in the motor equivalence theory.

We provided two navigation techniques, body-turn based and action-transferred based ones, and demonstrated the benefits of our approach by evaluating these two navigation techniques for spatial knowledge acquisition in several empirical studies. We also developed our own walking-like navigation technique, *Sensor- Fusion Walking-in-Place (SF-WIP)* because we needed a reference navigation technique for estimating the effect of the action-transferred navigation technique on spatial knowledge acquisition compared to that of a walking-like navigation technique.

We performed empirical user studies and the experimental results showed that body-turn based navigation technique was more effective for survey knowledge acquisition in a large-scale virtual maze, compared to a wand-joystick based common navigation technique (JS, i.e., non-body-based and non-walking-like navigation technique). However, no significant difference was found for route knowledge acquisition while the SF-WIP was more effective than the JS for both route and survey knowledge acquisition. The results of the SF-WIP were compatible to the results from other studies (using walking-like navigation techniques).

The action-transferred navigation technique, named *Finger-Walking-in-Place (FWIP)*, was more effective for both route and survey knowledge acquisition than the JS in the same large-scale, large-extent and visually impoverished virtual maze. In addition, our empirical studies showed that the SF-WIP and the FWIP are similarly effective for route and survey knowledge acquisition, suggesting that human's spatial learning ability is still supported by the transferred action (FWIP) as much as the original action (SF-WIP).

Since there was no significant difference between FWIP and SF-WIP but the FWIP showed the better effect than the JS on spatial knowledge acquisition, we can infer that our action-transferred approach is useful for designing convenient and effective navigation techniques for spatial learning. Some design implications are discussed, suggesting that our action-transferred approach is not limited to navigation techniques and can be extensively used to design (general) interaction

techniques. In particular, action-transferred design can be more effectively used for the users with disabilities (unable to use of a part of the body) or for fatigue/convenience reasons.

Related to our theoretical reasoning, we established another user study to explore if the transferred action is still coupled with the perception that is known as coupled with the original action. Our study results supported that there was a close connection between distance perception and transferred action as literature suggests.

Thus, this dissertation successfully supports our theoretical observations and our action-inspired approach to design of convenient and effective navigation techniques for spatial learning through our empirical studies. Although our conclusion is drawn from the empirical studies using a couple of NavTechs (body-turn and FWIP), and is therefore not the direct evidence at the neural level, it should be notable that our action-inspired design approach for effective spatial learning is strongly supported by the theories that have been demonstrated by a number of studies over time.

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Chapter 1

Introduction

1.1 Background and Motivation

Virtual reality (VR) is capable of providing realistic 3-dimensional (3D) simulated environments where people interactively act and perceive different sensory information. 3D virtual environments (VEs) have been effectively used for training and learning applications. Some military applications [48] include training land-navigation skills and learning layout of a target space and routes through large buildings. Firefighters can be trained in various disaster situations without real settings. For example, navigating smoke-filled buildings to rescue people from dangerous incidents and extinguish hazardous fires, not only must be carried out in specific situations, but also requires the firefighters to assimilate detailed spatial knowledge (e.g., spatial layout and shortest-route for exits) of the buildings. By allowing people to explore large-scale datasets, such as astronomical, biomedical, and seismic data [65], and ecological settings, such as scientific museum and zoo [8], VEs can help enhancing educational efficacy. For the public applications, such as touring museums, art galleries or historic places in foreign countries, navigation is necessary because people need to visit the numerous places and see the art products or historic products. Thus, navigating virtual space among other application-specific tasks is an indispensable task for many training and learning applications in VEs even when navigation itself is not the main objective of the applica-

tions.

For successful navigation in large-scale virtual environments (VEs), accurate spatial knowledge is required. Otherwise, people would get lost. By acquiring accurate spatial knowledge, people can effectively understand spatial layout and objects in environments [75]. In addition, spatial knowledge acquired from a large-scale VE can effectively be transferred to the real world activities [76, 108, 111]. Consequently it becomes important that navigation techniques (NavTechs) effectively support people to acquire accurate spatial knowledge for successful navigation in large-scale VEs.

As the evolutionary history of modern humans shows that walking was the only mode for our ancestors to move [112], it is considered that our most natural form to navigate is bipedal walking in the real world. In order to adopt the walking form for navigating in VEs, a number of walking-like NavTechs have been introduced, such as walking-in-place [25, 46, 90, 100, 113], redirected walking [73], treadmill-based walking [18, 20, 39], as well as natural walking [106, 109]. Moreover, the effect of these walking-like NavTechs on spatial knowledge acquisition including path integration has been demonstrated in several studies [15, 39, 47, 86, 109, 123].

However, there are some issues that make the walking-like NavTechs less commonly used. The potential issues of *real walking* involve requirement of large controlled-space covered by tracking system configuration [106]. Otherwise the second person (guider) should follow the first person (user) to carry tracking devices [109]. *Redirected-walking* [73, 74] has been studied and improved by several researchers [11, 67, 93, 94]. However, as indicated in [86], the current form of redirected-walking employed for effective spatial learning may cause additional cognitive loads due to virtual distractors that may not be acceptable in some VE applications. *Walking-in-place (WIP)* is requiring relatively small controlled-space and less complex system configuration, compared to the other walking-like NavTechs. However, the WIP NavTechs still present some other issues, such as start-stop latencies and unsupported dynamic walking-speed (e.g., LLCM-WIP [25] and GUD-WIP [113]). Although Kim *et al.* introduced *sensor-fusion walking in place* [46] to resolve the issues of latency and unsupported dynamic walking-speed, it still has some limitations

such as no support for walking-backward or sidestepping. *Treadmill-based walking* seems closer to natural walking than the other walking-like NavTechs supporting effective spatial knowledge acquisition [39, 86]. However, it requires not only very large and complex system configuration but also a user to wear a safety harness.

The most common and unresolved issue of various walking-like NavTechs is whole-body fatigue induced from continuous movement of the whole-body (legs, in particular), especially when navigating large-scale VEs to acquire spatial knowledge. The whole-body fatigue can cause deterioration of mental activity as well as decrease of physical performance [26, 115]. This whole-body fatigue issue of walking-like NavTechs has not yet intensively studied in VEs (*cf.* [29]) because the main focus of designing walking-like NavTechs has been on maximizing the advantage of body-based sensory cues (e.g., proprioceptive and vestibular cues) closer to natural walking. Although whole-body fatigue induced by walking in the real world would be natural to people, people need not to go through the same amount of whole-body fatigue in VEs.

We need to consider the issues described above to successfully adopt walking-like NavTechs for effective spatial knowledge acquisition in VE applications. On the other hand, simple and convenient NavTechs, for example, using wand and joystick devices in immersive VEs and keyboards and mice in desktop VEs, are more popular and commonly used. However, these simple and convenient NavTechs result in less effective spatial knowledge acquisition [15, 39, 86]. In this dissertation, the three types of issues of walking-like NavTechs are used to provide the operational definition ¹ of *convenient navigation technique*. A convenient navigation technique is defined as the navigation technique with less body-fatigue (or tiredness), less required spatial size, and less complexity of system configuration, compared to walking-like navigation techniques.

Thus, there are design trade-offs between the walking-like and the non-walking-like common NavTechs, i.e., the walking-like NavTechs support effective spatial knowledge acquisition, but less convenient use; the common NavTechs are simple and convenient to use but less effective in spatial knowledge acquisition.

¹The operational definition would serve the purpose of providing clarity to the reader.

The trade-offs lead to a research question, *how can we design a convenient navigation technique providing effective spatial learning with reduced whole-body fatigue, controlled space size, and/or system-configuration complexity?* We address the answer through this dissertation.

1.2 Research Objectives

From the literature (details are in §2.2, §2.3 and §2.4), we found that the most common approach to designing NavTechs to support effective spatial knowledge acquisition was to design walking-like NavTechs for maximizing the advantage of body-based sensory cues (e.g., proprioceptive and vestibular cues) closer to natural walking. There has been no other attempt to propose a new approach to designing effective NavTechs to improve spatial knowledge acquisition in VEs. Hence, the issues, whole-body fatigue, large-controlled space, and complexity of system configuration, of walking-like NavTechs still remain.

The main objectives of this dissertation are to: (1) provide a new approach to designing new NavTech(s) that can conveniently and effectively support people to acquire accurate spatial knowledge, (2) implement the NavTech(s) with the approach and demonstrate the usability of the developed NavTech(s), and (3) evaluate the effect of the NavTech(s) on spatial knowledge acquisition through empirical studies with human subjects. Specifically, the proposed approach should be able to explain how we can resolve the design trade-offs between walking-like and non-walking-like (common) NavTechs, as indicated in §1.1. That said, the developed NavTechs should be able to address the issues of walking or walking-like NavTechs. In addition, the evaluation should be able to demonstrate that the developed NavTechs are effective for spatial knowledge acquisition, compared to the common NavTech(s).

For these objectives, the specific research questions in this dissertation are:

- *RQ1: What are possible approaches to designing NavTechs for effective spatial knowledge acquisition?*

This question includes where we can start to propose a new design approach. We started by looking at previously proposed solutions and some theories to understand human spatial learning. After reviewing literature and theories, we proposed an action-inspired design approach grounded in theories to address the key research question. Details are provided in Chapters 2 and 3.

- *RQ2: How can we develop the NavTechs with the approach addressed in RQ 1?*

This question includes how to design and implement a new NavTech with the new approach proposed. We answered this question by providing the detailed process about how we can come up to developing the NavTechs based on the proposed approach. Details are described in Chapters 4 and 5.

- *RQ3: How can we assess spatial knowledge acquisition with the developed NavTech(s)?*

This question is about what metrics would be chosen for assessing spatial knowledge acquisition. There are many different measurements to assess the performance of spatial navigation, such as route replication, searching time, direction estimate by pointing, traveled distance, distance estimate, map sketches, and object recall. However, these measurements are not always appropriate and some measures are dependable each other in different types of virtual space. We discussed about these measurements and provided our own assessment of spatial knowledge acquisition. Details are provided in Chapter 4.

- *RQ4: Is the perceptual ability dependent on the original action still maintained by the transferred action?*

Related to our theoretical reasoning to answer *RQ1*, we explored if the transferred action is still coupled with the perceptual ability that is known as coupled with the original action. If so, a specific perceptual ability dependent on the original action will be still maintained by the transferred action. Details are provided in Chapters 6.

1.3 Dissertation Organization

In Chapter 1, we provide the background and motivation of our research, including its significance. We describe our research objectives including specific research questions. The rest part of this dissertation is designed to address the research questions.

In Chapter 2, types of spatial knowledge and its general development process during navigation are explained. Previous NavTechs and empirical study results on spatial knowledge acquisition are reviewed through literature survey.

In order to obtain a clue to the first research question (*RQ1*), several theories are explored in Chapter 3. Our theoretical reasoning integrating our understanding with the theories and relevant literature suggests two types of action-inspired approach: body-turn based and action-transferred approaches.

In Chapters 4 and 5, the proposed body-turn based and action-transferred approaches are evaluated through empirical studies with human subjects. These two chapters provide the answers to the second (*RQ2*) and the third (*RQ3*) research questions. New interaction techniques including sensor-fusion walking in place and finger-walking-in-place techniques are designed in order to perform comparative studies and demonstrate the effectiveness of the proposed approaches to the research questions. It is also discussed how the demonstrated action-transferred approach for the NavTech design can also be used for designing other interaction techniques, which suggests design guidance.

In Chapter 6, related to our theoretical reasoning in Chapter 3, we present another comparative user study designed to explore if the transferred action is still coupled with the perceptual ability that is known as coupled with the original action. This chapter will suggest the possible answer to the fourth research question *RQ4* by supporting our theoretical reasoning.

In Chapter 7, overall summary and conclusion of this dissertation are presented. The original contributions are summarized, followed by future work.

Chapter 2

Literature Review

In this chapter, we provide the overall background of spatial knowledge and the relationship between spatial knowledge acquisition and navigation. Previously proposed navigation techniques (NavTechs) and the results of empirical studies on spatial knowledge acquisition are reviewed. Finally, we discuss some limitations of the previously proposed approaches about the development of NavTechs and the evaluation methods on spatial knowledge acquisition.

2.1 Spatial Knowledge and Navigation

Spatial knowledge acquisition during navigation can be considered as a learning process¹ through interaction between people and environments. Spatial information, such as location information of objects, spatial layout of an environment or route information to exits, is (actively) perceived, stored in the human memory, and then used to take the next action aiming for achieving a goal in a given situation. By this learning process, spatial knowledge is continuously updated and more accurately developed during navigation.

¹“Spatial learning encompasses all formation of memories that permit later discrimination of place by reference to the surroundings, and discrimination of position as defined by the relative orientation of the learner” [13]

Spatial learning for a certain environment can be trained. For example, navigating in smoke-filled buildings to rescue people from dangerous incidents and extinguish hazardous fires, not only must be carried out in a specific context, but also requires the firefighters to assimilate detailed spatial knowledge (e.g., spatial layout and shortest-route for exits) of the buildings. If the firefighters are trained in the similar context, they can acquire spatial knowledge about the buildings, and the acquired spatial knowledge can be more accurate over training. The firefighters would learn what to act or what should not be acted at a certain location, or where to move for the exits in the smoke-filled buildings.

In order to explain the process of how spatial knowledge is acquired and represented, Siegel *et al.* [89] presented Landmark-Route-Survey (LRS) model in 1975. According to the model, people first learn to recognize landmarks, such as unique and magnificent buildings or natural landscapes, in the unfamiliar environment. People associate their location in the environment with reference to these landmarks – *landmark or declarative knowledge*. After people are familiarized with these landmarks, they can learn how to travel from one location to the other – *route or procedural knowledge*. Route knowledge can be acquired from learning what actions they take, as well as remembering landmarks [17]. People who acquired route knowledge may be able to travel the learned route comfortably without relying on landmarks [16]. However, with only route knowledge, people cannot find the optimal route and cannot build the mental map (i.e., cognitive map [103]) of the environment. As a final step, people can form *survey (or configurational) knowledge* that is a mental presentation of a map of the environment. People can develop survey knowledge (or cognitive map) by sufficient experience, including integrated route knowledge on different routes, in the environment.

However, some studies in modern research related to environmental learning demonstrated that route knowledge can be developed prior to landmark knowledge [30] or even without landmarks at all [1]. Survey knowledge can be simultaneously developed with route knowledge [62]. In 1998, Montello [60] suggests an alternative development process of spatial knowledge: i.e., three types of spatial knowledge can be continuously developed, and landmark or route knowledge cannot independently exist. Although there is controversy in development of spatial knowledge, it would

be useful to distinguish the different types of spatial knowledge because the accuracy of each type of spatial knowledge should be measured using different metrics (e.g., route replication for route knowledge or sketching the layout for survey knowledge).

One might wonder why people should navigate to acquire spatial knowledge. Actually, people can acquire spatial knowledge from several different sources [61], which can be divided into direct and indirect sources². Direct sources are non-symbolic, including sensory-motor experience through spatial navigation by walking or driving in the environment. These sensory-motor experiences can be divided into two types, mechanically-assisted (e.g., riding in a car or bicycle) and unassisted ones (e.g., crawling, walking or running). Indirect sources are symbolic or mediated (by Gibson [32]), requiring mental encoding. These indirect sources can present spatial information in several different forms, such as maps, blueprints and schematic diagrams.

Direct and indirect sources are differently encoded into memory because they need different cognitive process, as leading to different types of representations. For example, knowledge acquired from maps is affected by one's orientation while knowledge learned from navigation through an environment has orientation-free representation [118]. Moreover, according to the study of Thorndyke *et al.* [102], navigating through a space is the best way for landmark and route knowledge acquisition, while maps are the optimal solution to acquire survey knowledge rapidly. However, Thorndyke *et al.* [102] also found that navigation-trained survey knowledge exceeded map-trained survey knowledge in terms of accuracy. Thus, (spatial) navigation would be the more optimal solution to acquire the more accurate spatial knowledge.

As Ruddlet *et al.* [85] argued, the distinction between the different types of spatial knowledge can be useful to measure the different accuracy of spatial knowledge with different metrics. There can be several measurement methods for assessing the acquired spatial knowledge, including route replication [39, 69], searching time [77], direction estimate by pointing [15, 86, 109], traveled distance [86], distance estimate [86], map sketches [96, 123], and object recall [96]. Among them, the

²Spatial learning is also divided into primary and secondary learning [70], corresponding to direct and indirect sources.

route replication and the map-sketch tasks are generally known as holistic methods for assessing route knowledge and survey knowledge, respectively. Route replication can include measuring the number of wrong turns, route traversal time, route traversal distance and the number of misidentified landmarks. On the other hand, directional accuracy, distance estimation and positions of landmarks can be measured based on the map-sketches. However, it would be difficult to get consistent results from multiple measurements with a limited number of participants.

2.2 Navigation Techniques (NavTechs)

We review various NavTechs that have been proposed for spatial navigation tasks in VEs. In particular, the NavTechs are reviewed for two categories, walking-like and non-walking NavTechs. Non-walking NavTechs include some body-control based NavTechs as well as steering-metaphor and keyboard-mouse based NavTechs.

2.2.1 Walking-like NavTechs

Walking-like NavTechs have been demonstrated to enhance the level of presence [104] and the performance of wayfinding or spatial knowledge acquisition tasks [15, 39, 47, 86, 109, 123], compared to non-walking NavTechs (especially, wand and joystick based NavTechs in immersive VEs). There are several types of walking-like NavTechs, such as *natural walking* [84, 109, 110], *treadmill-supported walking in place (WIP)* [18, 39], and *real walking in the limited space* [38, 66, 74].

- **Natural walking** is the most natural NavTech for spatial navigation in VEs as human beings are natural to have the ability to walk upright on two legs through over-learning in the real world. It can support the higher sense of presence [104] and the better spatial knowledge acquisition [109] in VEs, compared to the other NavTechs. Natural walking has been used in several comparative studies by using large-scale but small-extent virtual space [84, 96, 104].

However, in order to navigate with natural walking in large-scale and large-extent virtual space, a huge controlled-space (i.e., tracked space) [106], corresponding to the spatial size of the given virtual space, is required. When natural walking is used in outdoor space [109], the evaluator should follow the human subject to carry tracking devices. In addition, there are many risky situations, such as bad weather, uneven ground, etc. Thus, natural walking would be preferred when navigation is performed in small-extent space.

- **Real walking in limited space** can be used alternatively to achieve natural walking in limited physical tracking space available. While a user maintains her/his rotation and translation in the small and physical space, the virtual scene is translated and rotated about the user with the bigger scale than the user's physical movement. This type of NavTechs include Redirected-Walking [74], scaled-translational-gain [116], seven-league-boots [38], and Motion Compression [64]. Ideally, it would work that the user does not notice this difference because the algorithm exploits the limitations of human perceptual mechanisms for sensing position, orientation, and movement. However, it sometimes introduces a conflict between visual perception and proprioceptive feedback [95]. As indicated in Ruddle *et al.* [86], the most recently implemented redirected-walking can inhibit users performance because it uses specific virtual distractors in order to guide the physical trackers boundary, causing distraction of users attention during reorientation [67]. Interestingly, real walking NavTechs proposed for the limited physical space have not been yet used for studying the effect on spatial knowledge acquisition, except for Peck *et al.* [67].
- **Walking-in-place (WIP)** has a diversity to be implemented. For example, the system described by Slater [90] used a neural network based on head-tracking data to distinguish walking in place from other movements in the virtual environment. Slater *et al.* reported that this works reliably even without customization for individual gaits as the head moves significantly during each stride during navigation. However, the actual extent of head motion is considerably smaller unless the walking is quite animated. Due to this reason the next other approaches use tracking of the legs rather than only the head. For example, Temple-

man *et al.* developed a virtual locomotion interface, called Gaiter, for military simulators [100]. The motion of legs was detected by sensors placed on shoe insoles, and 6-DOF trackers attached to the knees sensed the distance and direction of leg motion. The system was quite flexible and could detect a variety of locomotion types, e.g., slow walking or fast running, important for military operations. However, detection of a step during forward motion required to wait until the knee reaches a certain point. This can be unacceptable latency (e.g., 400ms when walking at a moderate pace as reviewed in [25]) for some applications, although the later work for Gaiter can reduce the half-step's latency as indicated in [25]. In addition, there are some usability issues of Gaiter reported in [88]. For example, additional equipment such as rope and pole harness interfered with the subjects' stepping. The heavy and noise head-mounted display (HMD) also bothered some subjects for doing the given tasks, as well as its narrow field of view (FOV). Thus, [88] shows an example with respect to how inconveniently walking-like navigation techniques can be used.

Low-Latency Continuous-Motion Walking-in-Place (LLCM-WIP) [25] and Gait Understanding Driven Walking-in-Place (GUD-WIP) [113] NavTechs have recently been proposed in 2008 and 2010, respectively. LLCM-WIP [25] is also sensor-based WIP technique as Gaiter [100] was proposed, but reduces the latencies when starting and stopping of walking. However, users movements can be still restricted by a wire or cable tethered to her/his body. This aspect can cause a lower level of presence and consequently affect navigation performance. Wendt *et al.* proposed GUD-WIP by using an optical motion capture system. This approach may support more free motion. However, it is hardly applicable to projection-based VEs (e.g., CAVE) due to the difficulty of system configuration. In addition, their approach introduced a relatively long stop-latency (approximately 500ms) than that of LLCM-WIP. Thus, development of WIP NavTechs is still challengeable and on-going research to make robust NavTech in VEs, compared to the common NavTech (e.g., wand and joystick device based 'flying' NavTech).

- **Treadmill-supported WIP** (e.g., treadmill [18, 37], cyberwalk [19, 91] or VirtuSphere [52]) allows a user to walk in place close to natural walking. Although the user motion is simi-

lar with that of “walking-in-place”, the treadmill helps to distinguish two movements, move forward, and move backward. The original purpose of this interface is to train infantry soldiers [12, 37] by varying the slope of the treadmill. Compared to natural walking technique, it takes smaller space, regardless of how large the virtual world is. Since it is basically supported by a device, some usability problems can occur when the user’s motion quickly changes for sudden stop, start or turn due to significant inertia of the treadmill. In general, for protection in case of a fall, the users wear a safety harness [54] that takes additional effort and requires non-realistic forces exerted by the legs.

2.2.2 Non-Walking-like NavTechs

- **Pedaling-based NavTechs** consist of a vehicular and body-based navigation control. The Uniport is a unicycle-like device developed by Sarcos Research Corporation (reviewed in [18]) for an infantry training program. For example, the direction of motion is controlled by twisting of the user’s waist and thighs. It has some benefits, including that the user’s hands are free to manipulate other things. However, it is reported that there are some usability issues, such as difficulty of maneuvering over short distances and awkward direction control [18]. Pointman [101] was proposed as an infantry training navigational interface for desktop VEs. The Pointman user interface consists of a conventional dual-joystick gamepad for controlling directional motions and handling weapons, sliding foot-pedals for controlling translation while providing realistic tactical feedback, and head tracker for providing the direction where the user is looking. Since it was developed not only for navigation but also for object manipulation to train infantry soldiers, it has not been demonstrated that the Pointman is effective for spatial knowledge acquisition.
- **Body-control based NavTechs** can be realized by using motion-platforms. For example, Peterson *et al.* [69] present a body-control based NavTech, named Virtual Motion Controller (VMC). A user of the VMC controls the direction and speed of movement by the user’s weight or distance from the center of the device. Peterson *et al.* [69] showed that VMC was

significantly effective on survey knowledge acquisition in the task of finding a shortest path, but not route knowledge acquisition in the route-replication task, compared to the joystick-based flying technique. For another example, Fairchild *et al.* [24] present a leaning technique where both the user's torso and head are tracked. The application then uses this information to determine when the user is leaning, and in which direction he/she is leaning. The user then translates through the virtual world in the direction of the lean.

These body-control based NavTechs involve the user's body that may lead to an enhanced sense of presence by using vestibular cue. Another benefit of these body-control based NavTechs is that the user's hands are not involved in navigation, making it possible for the user to move while performing another task such as selection or manipulation of objects. Thus, within the context of navigation tasks, these body-control-based NavTechs support hand-free interaction mode. However, it is reported that the position control can be less precise compared to the hand-based control, for example, using a joystick [68]. In addition, it has not been demonstrated that body-control based NavTechs are effective for route knowledge acquisition.

- **Steering-metaphor based NavTechs** can be implemented in several different forms using gaze, pointing, or steering props. The most common method to implement this type of NavTechs is based on a wand and joystick device. With this device, users can not only control direction, but also control navigation speed by adjusting the amount of force to push the joystick. That said, the displacement of the joystick controls the rate-based speed. Steering-metaphor based NavTechs provide easy and convenient ways to navigate a virtual world, but the effect on the level of presence [104] and the effect on spatial knowledge acquisition [39, 77] are less, compared to the walking-like NavTechs. Another downside is that users may not have one or both hands free for manipulating something else, such as object selection or manipulation, or system control.
- **Keyboard-mouse-based NavTechs** are usually adopted for desktop VEs. Key presses to move through the environment are used, and a mouse can be additionally used to change the

viewpoint. This type of NavTechs are rarely adopted for studying in immersive VEs (IVEs) because they may be cumbersome for the users or hindering users activities in IVEs. Hence, these keyboard and mouse-based NavTechs have been mainly employed in psychological experiments, for example, for comparing the absence of body-based sensory cues (e.g., proprioceptive and vestibular cues) [83, 84] with walking-like NavTechs that support full-body based sensory cues.

There are some other types of non-walking-like NavTechs, such as target-based and route-planning based NavTechs [9] that are rarely used for effective spatial knowledge acquisition in VEs.

2.3 Previous Study-Results on Spatial Knowledge Acquisition

There have been several comparative user studies performed to demonstrate the effectiveness of walking-like or body-control based NavTechs in spatial knowledge acquisition. In particular, there are more common types of comparisons, such as walking-like versus non-walking-like NavTechs [15, 39, 83, 84, 86, 109] or non-walking but body-control-based versus non-body-control-based NavTechs (e.g., wand and joystick based common NavTech or keyboard and mouse-based NavTechs). However, as described in Ruddle *et al.* [86], the comparative studies sometimes show the incompatible results.

For example, Ruddle *et al.* and Waller *et al.* demonstrated that walking-like NavTechs can improve spatial knowledge acquisition, compared to non-walking and non-body-control based NavTechs (e.g., wand and joystick based NavTechs) through a series of user studies [83, 84, 86, 109]. On the other hand, Suma *et al.* [96] showed no difference between a natural-walking NavTech and steering-metaphor based NavTechs (i.e., gaze-based and pointing-based direction control) in a cognitive task, remembering the locations of objects, after navigating the maze. Considering that many previous studies produced the same findings [15, 39, 83, 84, 86, 109] while Suma *et al.* [96] showed the different result, one might consider some other factors besides the used NavTechs affecting the result of [96]. A possible factor may be about the background of the recruited par-

ticipants. Interestingly, Suma *et al.* [96] recruited the participants from Computer Science courses for Experiment 1 and Experiment 2 and Psychology courses for Experiment 2. The distribution of the participants recruited from two different courses was not reported in [96]. One may raise a question that the task performance might not be affected by the used NavTechs if the participants were already good at controlling computing devices and already knew how effectively they used the steering-metaphor based interfaces. As another possible factor, the walking NavTech with the heavy head-mounted-display (HMD) in Suma *et al.* [96] might not be comfortable for users to control virtual movement speed as much as the steering-metaphor based NavTech. For example, the participants might tend to move less and slower due to the heavy HMD [88] and the tethered cables. These intentions, if any, would result in some additional cognitive loads besides the main tasks. Since there was no further discussion reported in Suma *et al.* [96], further study would be necessary in order to explain the different results more thoroughly.

Although Suma *et al.* [96] showed the different result, it is generally assumed that walking-like or body-control based NavTechs support more effective spatial knowledge acquisition, compared to non-walking and non-body-control based NavTechs as demonstrated in the other studies [15, 39, 47, 86, 109, 123].

Another interesting different result can be seen between two studies of Riecke *et al.* [77] and Ruddle *et al.* [83, 86]. Ruddle *et al.* [83, 86] showed that body-control based translation (i.e., bipedal walking) is necessary for establishing effective cognitive map in direction and distance estimates. On the other hand, Riecke *et al.* [77] showed that body-control based rotation would be enough for effective virtual navigation in reducing searching time. The experiment setup including virtual space and measured tasks in Riecke *et al.* [77] were almost identical to those of Ruddle *et al.* [83], except for the compared NavTech and display system; Ruddle *et al.* [83]: walking with HMD versus desktop-computer display with keyboard and mouse; Riecke *et al.* [77]: walking with HMD versus HMD with a joystick. Hence, the different compared NavTechs and display systems might produce the different results in [77, 83].

As presented in Ruddle *et al.* [86], different spatial extent combined with visual richness of

an environment can affect the results. For example, in small-scale and small-extent space with visually-rich information, Klatzky *et al.* [47] showed that body-control based rotation is critical for accurate path integration, compared to using the body-control based translation or non-body control for navigation. On the other hand, Ruddle *et al.* showed that both body-control based translation and rotation played the more important role in a search task, compared to using the non-body-control or body-control based rotation only in large-scale and large-extent but visually-impooverished space [84] and visually-rich space [86]. Moreover, from the studies [47, 84, 86], we also observed that the assessment methods due to the different tasks, e.g., path integration versus search task, can cause the different results.

Thus, based on our literature review, we found that there can be possible factors, such as spatial extent, assessment methods, speed control and visual richness of an environment, affecting the study results when the comparative studies are performed to investigate the effect of NavTechs on spatial knowledge acquisition.

2.4 Issues of Walking-like NavTechs

Our literature review (§2.3) supported the general assumption that walking-like or body-control based NavTechs are preferably proposed to support effective spatial knowledge acquisition, compared to non-walking and non-body-control based NavTechs. Although there are different claims which one between body-turn (i.e., body-control based rotation) only and bipedal walking with body-turn is supporting the better performance of spatial knowledge acquisition tasks, we observed that most efforts of designing NavTechs to support better spatial knowledge acquisition seemed aiming for a common approach, i.e., designing walking-like NavTechs for maximizing the advantage of body-based sensory cues (e.g., proprioceptive and vestibular cues) combined with visual sensory cues, closer to natural walking. For example, WIP NavTechs [25, 113] have been improved by reducing the start and stop latencies since the original concept of WIP was proposed [90]. Treadmill-supported WIP is also in developing [91] to support unconstrained natural

walking on a treadmill although a safety harness is still necessarily work for reducing any safety risks.

However, there are some issues that make the walking-like NavTechs less commonly used. We found that each type of walking-like NavTechs has some different issues to be commonly adopted for many VE applications.

The potential issues of *natural walking* NavTech include requirements of large controlled-space and relevant tracking system configuration. As shown in [106], for navigating a large-virtual-space, the large physical space corresponding to the virtual-space is required. Otherwise, the second person (guider) should follow the first person (user) to carry tracking devices [109]. *Real walking in limited space* can resolve these issues, and especially redirected-walking NavTech has been studied and improved by several researchers [11, 67, 94, 93] since its concept was introduced and implemented [74]. However, as indicated in [86], the current implementation of redirected-walking NavTechs may cause additional cognitive loads due to virtual distractors that may not be acceptable in some VE applications. Although Suma *et al.* [97] combined a number of several existing redirection techniques with a specifically designed virtual space to support natural walking in the physical tracking area with a limited size, it may only work for certain scenarios [97].

Walking-in-place (WIP) NavTechs are requiring relatively small controlled-space and less complex system configuration, compared to the other walking-like NavTechs. However, the most recently implemented WIP NavTechs produced some other issues, such as start-stop latencies and unsupported walking-speed (e.g., LLCM-WIP [25] and GUD-WIP [113]). In addition, WIP NavTechs only support one direction of movement, i.e., a user can only move in the heading direction, but not move backward or move aside. *Treadmill-supported WIP* NavTechs seem the best candidate closer to natural walking in terms of supporting effective spatial knowledge acquisition. However, it requires a user to wear a safety harness as well as very large and complex system configuration.

The most common and unresolved issue among various walking-like NavTechs would be whole-body fatigue induced from continuous movement of the whole-body, which result in deterioration of mental activity as well as decrease of physical performance [26, 115]. This whole-body fatigue

issue of walking-like NavTechs has not yet intensively studied in VEs (*cf.* [29]) because the main focus of using walking-like NavTechs was on maximizing the advantage of body-based sensory cues as much as natural walking can provide, but not on reducing whole-body fatigue. Although whole-body fatigue induced by (natural) walking in the real world would be natural to people, people need not to go through the same amount of whole-body fatigue in VEs if there is a NavTech that is effective for spatial knowledge acquisition and convenient in use. Any additional training, such as physical exercise or application-specific missions, can be performed separately from spatial learning tasks.

These issues should be considered to successfully adopt walking-like NavTechs for effective spatial knowledge acquisition in VE applications. Hence, it would be needed to propose a new approach to design effective and convenient NavTechs for spatial knowledge acquisition in a different way from the previous approach.

2.5 Chapter Summary

We provided overall background of spatial knowledge and the relationship between spatial knowledge acquisition and navigation. We understood that the different types of spatial knowledge should be differently assessed. Literature also supports that the importance of navigation is to acquire effective spatial knowledge.

Then, we reviewed different types of NavTechs divided into walking-like and non-walking-like NavTechs, and the previously performed comparative studies. Our review supports the general assumption that walking-like NavTechs support better spatial knowledge acquisition, compared to the non-walking and non-body-control based NavTechs.

Although there were many variations of walking-like NavTechs to support effective spatial knowledge acquisition, the traditional approach to improve walking-like NavTechs cannot resolve some potential issues, body-fatigue, large-controlled space and complex system configuration, while maintaining the effectiveness in spatial knowledge acquisition. Hence, non-walking-like and non-

body-control based NavTechs are still more popular and commonly used as NavTechs – *common NavTechs* – while the common NavTechs result in less effective spatial knowledge acquisition [15, 39, 86, 109]. Thus, design-trade-offs are inevitably introduced between the walking-like and the common NavTechs, i.e., the walking-like NavTechs support effective spatial knowledge acquisition, but less convenient use; the common NavTechs are usually simple and convenient to use but less effective in spatial knowledge acquisition. Thus, this chapter supports our research motivation to address the design-trade-offs. That said, expected NavTechs should be able to reduce whole-body fatigue, controlled space size, and/or system complexity, yet maintain the effective spatial benefits including spatial knowledge acquisition.

From our literature review, we also observed that there could be different results due to some other factors, such as spatial extent, assessment methods, speed control, and visual richness of an environment. The spatial extent and visual richness of an environment would be chosen according to the demands of the target applications. The speed control for virtual movement should be evenly fair for the used NavTechs. Preferably, the speed control should be comfortable enough, meaning that users should be able to control their movement speed as individual users feel comfortable. Any additional cognitive loads should be considered. For example, unexpected latencies and intentional less movement due to heavy or bulky interface systems would induce some unnecessary cognitive loads. The assessment methods for spatial knowledge should be differently adopted for measuring different types of spatial knowledge, e.g., route and survey knowledge acquisition, respectively.

Interestingly, there was no study to show the consistent effectiveness of a NavTech in both route and survey knowledge acquisition tasks, and even there was very little research to attempt to measure different types of spatial knowledge [69]. If a NavTech is only effective in one type of spatial knowledge acquisition, another NavTech may be required for an application that demands the effectiveness in both route and survey knowledge acquisition. Hence, the expected NavTech would be effective for both route and survey knowledge acquisition.

Chapter 3

Proposed Approach

In the previous chapter, the review of prior research on designing effective navigation techniques (NavTechs) for spatial knowledge acquisition provided the background about what approaches to design of NavTechs have been proposed to improve spatial knowledge acquisition in virtual environments. Interestingly, most proposed NavTechs for the purpose of improving or enhancing spatial knowledge fall into a common approach, i.e., designing walking-like NavTechs to maximize the advantage of body-based sensory cues (e.g., vestibular or proprioceptive cues) closed to those of natural walking.

If we keep focusing on improving walking-like NavTechs to get better body-based sensory cues, it would be very hard to resolve the issues, e.g., large-controlled space, complex-system configuration and whole-body fatigue. Consequently, we cannot address our key question, *how can we design a convenient navigation technique providing effective spatial learning with reduced whole-body fatigue, controlled space size, and/or system-configuration complexity?* In order to find a new design approach, we rather focused on understanding human spatial learning because our ultimate goal is to improve human spatial learning not to improve walking-like NavTechs closer to natural walking.

3.1 Theoretical Background

3.1.1 Spatial Learning: Learning Cycle and Perception-Action Cycle

Spatial knowledge acquisition during navigation can be considered as a learning process¹ through interaction between people and environments. Spatial information, such as location information of objects, spatial layout of an environment or route information to exits, is (actively) perceived, stored in the human memory, and then used to take the next action aiming for achieving a goal in a given situation. By this learning process, spatial knowledge is continuously updated and more accurately developed during navigation. This type of learning process can be found in single-loop [2] learning and experiential learning [49] theories.

According to single-loop learning [2], when people have objectives achieved, they take actions so that they can receive information, and then take corrective action based on the received information (feedback). Argyris and Schön argue in single-loop learning that people have mental maps determining their actions, regarding how to plan, perform and review the actions in certain situations [3]. This single-loop learning was originally proposed to explain learning by individuals in an organizational context, the principle of which is based on the cyclic interaction between people and organizations with feedback. If we extend the range of organizations to environments, we can understand that single-loop learning explains how people acquire and develop spatial knowledge through the cyclic interaction between people, environments and resultant on-going updated knowledge.

On the other hand, the experiential learning theory [49] states that learning is founded on the experiences and self-reflection, i.e., ability to evaluate one's own experiences by observation. Kolb's experiential learning theory actually refers to four stages, concrete experience (CE), reflective observation (RO), abstract conceptualization (AC), and active experimentation (AE). In the CE stage, a person has an experience by executing a particular action, and then observes the effect of the

¹“Spatial learning encompasses all formation of memories that permit later discrimination of place by reference to the surroundings, and discrimination of position as defined by the relative orientation of the learner” [13]

action in the certain context and reflects on the experience in the RO stage. By understanding and learning about *why it happened* from the experience (AC stage), the person goes to the next stage, AE, by planning the next action, i.e., *what will I do next?* By performing actions reflected on the experience, the person enters the CE stage again. Thus, the core concept of the experiential learning theory is that we would not simply continue to repeat our mistakes, if any, without reflections after understanding the consequences of our action. This core concept of experiential learning can explain how people develop their spatial knowledge more accurately with increased experiences during navigation in an environment. For example, taking a wrong path (i.e., inaccurate spatial knowledge) can be corrected by the next action (e.g., going back to the previous position or finding a new route). Interestingly enough, experiential learning of spatial knowledge acquisition was already implied in [102] as increasing navigation experience in an environment develops more accurate memory representation about the environment.

The experiential and single-loop learning theories seem to suggest different stages for the learning cycle, but both theories implicitly refer to the perception-action cycle that is defined as, “perception-action cycle is a circular cybernetic flow of information processing between the organism and its environment in a sequence of goal-directed actions. An action of the organism causes an environmental change that will be processed by sensory systems, which will produce signals to inform the next action, and so on” [28]. We illustrate the similarity of the perception-action cycle and the two learning cycles in Figure 3.1. In single-loop learning (Figure 3.1b), *plan* and *act* can be combined by “planned action” i.e., “goal-directed action” and *review* means that people get feedback from the performed action, referring to receiving the perceivable information from the environment, which is updated by the performed action. Hence, the perception-action cycle (Figure 3.1a) can be corresponding to the single-loop learning cycle. Likewise, in experiential learning (Figure 3.1c), *AE* and *CE* can be combined by *planned action*, i.e., goal-directed action, and the role of *RO* is corresponding to *perception*. As the perception-action cycle is going through several cognitive processes, such as problem solving, reasoning, and decision making, the experiential learning cycle goes through *AC* to understand *why it happened*. Although human information process is not fully understood yet (*cf.* [14]), we can, at least, understand that perception and action play central roles

to process the information (i.e., knowledge acquisition) gained through the interaction between the organism (e.g., human) and its environment.

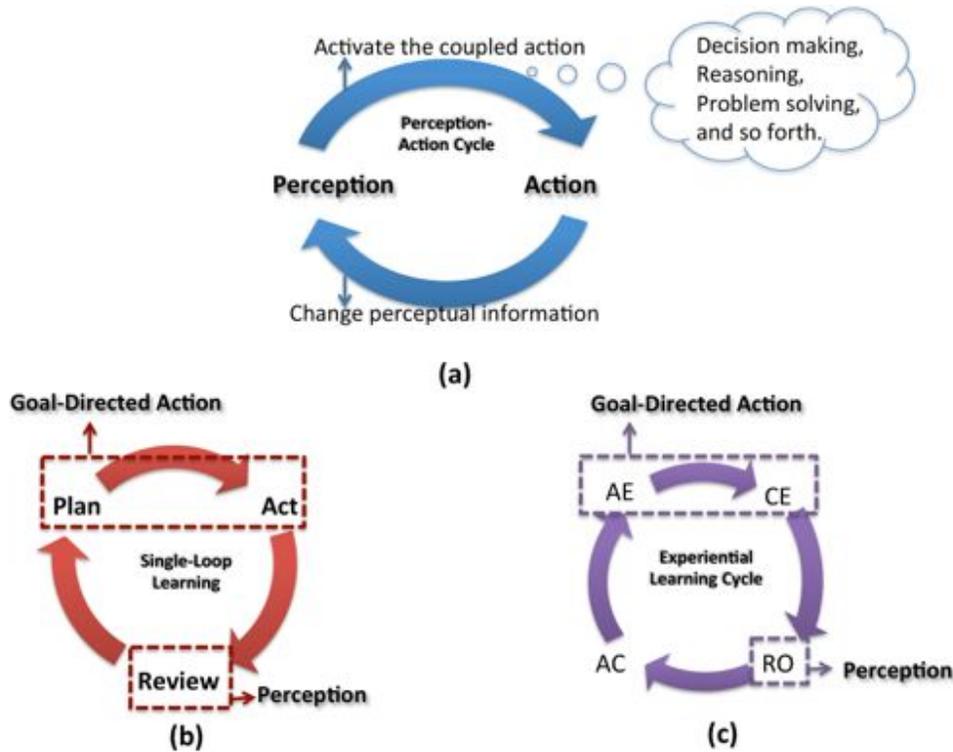


Figure 3.1: Similarity of the perception-action cycle (a) and the two learning cycles (b) and (c); (a) Perception-Action Cycle, (b) Single-Loop Learning Cycle [3], and (c) Experiential Learning Cycle [49] with four stages, concrete experience (CE), reflective observation (RO), abstract conceptualization (AC), and active experimentation (AE).

3.1.2 Perception and Action: Tightly Connected

The relationship of perception and action is also considered as a tight link to inform each other, as Roger Sperry, who is a neurophysiologist and Nobel Prize winner, argued that “perception-action cycle is a fundamental logic of the nervous system and perception and action processes are functionally intertwined” [92]. Since then, this relationship between perception and action has been supported by other theories, such as ideomotor theory and common coding theory, and

experimental psychology.

According to the ideomotor theory advanced in the middle of the 19th century, there is an association between the action's motor code and the sensory effects that the action produces [35]. Based on the theory, the study result by Elsner et al. [22] suggested that the perception of the sensory effect, learned by doing an action, activates the action which is associated with. It implies that this association occurs only if the action is performed by the user's voluntary action mode [35].

The common coding theory introduced by Prinz [71] states that perception (sensory information) and action (motor information) are stored in a shared representation system. Rieser *et al.* [80] also presents a model that action, perception and representation (i.e., cognitive map) are "coupled together as a functionally organized system with respect to perceiving space, acting in space, and learning and remembering space".

Gibson's [31] theoretical work in experimental psychology also explains this coupled relationship between perception and action (also known as perception-action invariant). For example, people during navigation continuously coordinate and adjust their actions based on feedback obtained from the continuous spatial and temporal information induced by the combination of the environmental structure and the actions. Successful navigation and accurate spatial knowledge acquisition can depend on this perception-action loop [99].

To sum up, spatial learning is explained by the concept of the tight link and the feedback cycle between perception and action, named *perception-action coupling*. People move around by perceiving egocentric (body-relative) and exocentric (environment-relative) spatial information. The perceived information can be dynamically updated by spatial movement (locomotion). By perceiving the environmental consequences, e.g., different direction and distance relative to the certain objects (or targets) in the environment, people can learn when, where and how to perform their actions. Thus, while people continuously perceive environmental consequences, including spatial information, people also understand what actions cause the environmental consequences.

3.1.3 Perception and Action: Core Elements of Spatial Learning

Our insights from the theories of learning and perception-action can be applied to explaining the effects of walking-like NavTechs for spatial learning, compared with (non-walking) common NavTechs. According to the concept of perception-action coupling, what we perceive and how well we perceive it depend on our action. As aforementioned, (bipedal) walking is the human's most natural form to navigate and to acquire spatial knowledge. Since *walking* is an over-learned action for people to perceive spatial information (e.g., orientation, distance or route), *walking* action has become tightly coupled to spatial perception in various environments. Therefore, walking-like NavTechs can effectively work for spatial learning.

In order to explain the spatial learning effect of walking-like NavTechs, it can be an alternative perspective to take the concept of perception-action coupling while most previous studies provided a different perspective that body-based sensory cues [109, 83, 107] are more important roles for supporting better spatial learning. It should be noticed that we are not claiming that the body-based sensory cues are less important for spatial learning, but suggesting another perspective that would be related to our new design approach described later.

Based on our insights from the theories of learning, action, and perception, we also observed that none of the theories says that biological effectors (i.e., body parts to execute an action) are not necessarily related to spatial learning, meaning that action-dependent perception or perception-dependent action plays a central role for spatial learning while neither one depends on the biological effectors. That said, perception-dependent action is needed not to be performed by specific biological effectors. This observation leads us to a new design clue that we may be able to design a convenient NavTech while the effectiveness of the NavTech in spatial learning remains the same as walking-like NavTechs, even when using different biological effectors. A neuropsychological theory, known as motor equivalence theory [50], supports this new design idea, as described in the subsequent section.

3.1.4 Motor Equivalence Theory: Concept of Action Transfer

We sometimes observe that right-handed people can perform writing text with a left-hand, or even with a foot without extra learning with different body parts. This simple example shows that the writing action can be transferred from the right hand to the left hand or the foot. The different body part (the left hand or the foot) can execute the same movement pattern (e.g., writing text) as what the right hand could do. The motor equivalence theory [50] can explain how this phenomenon is possible.

Lashley [50] first introduced the motor equivalence theory that has been supported by other robust studies [81, 98] using functional magnetic resonance imaging (fMRI). According to the motor equivalence theory, a performed action with an intention (i.e., goal-directed action) can be encoded as an abstract form representing a movement or motor pattern rather than a series of joint motion or muscle contractions [81]. The encoded abstract form can be performed using a different biological effector (i.e., body part) with the same intention. In other words, the abstract form can be transferred from the original effector(s) to other effectors.

For example, [81] used fMRI to examine the same brain activity patterns associated with a movement executed by different biological effectors. In [81], all participants were asked to perform general zigzagging and personalized signing movements either by the index finger or the big toe. Only in the signing condition with two different effectors, i.e., the finger and the toe, it was found that some common areas of the brain relating to the limb-independent were activated. The study result showed that certain brain areas can be activated by different biological effector systems when people perform goal-directed actions (e.g., signing action).

Thus, the motor equivalence theory suggests that an action can be transferred to different effectors while activating the neural machinery relating to the original action. This transferred action may be visibly different from the original action. However, two actions would contain a same motor pattern, i.e., abstract form [81]. In addition, other empirical studies have demonstrated that motor learning trained on a single effector system can be transferred to untrained effector systems in the

real world [27, 41]. Thus, the motor equivalence theory explains that (motor) leaning and transfer involve a common mechanism – neurally instantiated – that exists as an abstract form.

Even though the motor equivalence theory explains that the original action and the transferred action are neurally equivalent, it does not explain whether or not the spatial learning effect of the transferred action still remains the same as the original action. However, as we theoretically reasoned in the previous sections, our learning ability is dependent on *action* and *perception*, but not necessarily on biological effectors (body parts). Hence, we can expect that spatial learning effect dependent on an action would still remain even after the action is transferred to the other body parts.

3.2 Action-Inspired Approach

In the previous section, spatial learning is related to perception and action that are tightly connected and informing each other. Since our research purpose is to provide a new design approach of interactive NavTechs but not to provide perceptual information in the environment, our proposed approach is focusing on action rather than perception, called *action-inspired approach*.

Our theoretical reasoning suggests two important aspects, (1) the core elements of spatial learning are action and perception, but not body parts and (2) spatial learning effect is equally supported by the original action and the transferred action. Referring to these two aspects, there can be two types of action-inspired approach to designing convenient and effective NavTechs for spatial learning.

Firstly, we can simply replace translational or rotational control of walking-like NavTechs with more convenient control for navigation. Usually, translational control is performed by cyclic leg-movement while rotational control is performed by body-turn in walking-like NavTechs. We decided to replace translational control of walking-like NavTechs with the convenient control of common NavTechs while we keep rotational control of walking-like NavTechs; we call this action-inspired approach as *Body-turn based approach*.

Secondly, we can provide another action-inspired approach using the concept of “action transfer” as the motor equivalence theory suggests; we call this as *Action-transferred approach*.

In this chapter, we present details about these two types of action-inspired approach.

3.2.1 Body-Turn Based Approach

Walking-like NavTechs resemble natural walking, in that walking-like NavTechs provide body-controlled translation (*BodyTrans*), and rotation (*BodyTurn*) for navigation in VEs. *BodyTrans* is realized by cyclic movement of lower limbs (e.g., mainly two legs) while *BodyTurn* is realized by turning the whole-body in place. If we look close to the issues (§2.4) of the previously proposed walking-like NavTechs, we can find that these issues are more likely related to *BodyTrans*. For example, the large-controlled space [106] is required because the cyclic movement of two legs is to control one’s physical position in an environment. The complex system-configuration, such as treadmill [18, 39] or cyber-carpet [19] is demanded to detect the legs’ movements and apply the movements to the virtual movements correspondingly. The whole-body fatigue is in part caused by the continuous movement of two legs for translation of one’s physical position. Although whole-body fatigue induced by walking in the real world would be natural to people, people need not to go through the same amount of whole-body fatigue in VEs. Hence, we decided to replace translational control of walking-like NavTechs with that of common NavTechs while rotational control of walking-like NavTechs remains.

Our body-turn based approach basically combines *BodyTurn* of a walking-like NavTech with the transitional component of the non-body-control based NavTech (*NonBodyTrans*). If we use a wand and joystick based NavTech, *NonBodyTrans* is controlled by a joystick. With our body-turn based approach, we can easily resolve some issues presented from walking-like NavTechs. Since *BodyTurn* is usually obtained by turning in place, we do not need any large-controlled-space. Since the joystick-controlled translation is usually dedicated to most immersive VEs, we don’t need additional complex system-configuration. In addition, since relatively smaller muscle groups and

joints in the fingers to control the joystick are used for continuous translational control although *BodyTurn* still exists, the expected whole-body fatigue can be reduced than *BodyTrans* of walking-like NavTechs.

It would be not a new idea that body-turn would be effective for spatial knowledge acquisition. However, very few studies demonstrated the effect of *BodyTurn* without walking on spatial knowledge acquisition. Some studies showed the effect of *BodyTurn* in relatively simple spatial tasks, such as path integration in a triangle-completion task [5, 47] or target-finding task at a fixed position [51]. From the results of these studies with simple spatial tasks, it is not clear whether *BodyTurn* is effective to acquire spatial knowledge during navigation, especially in large-scale VEs. To the best knowledge of the author, there is only one study, Riecke *et al.* [77], showing the effect of physical body-turn without walking in a search task which is relatively complex task during navigation. By using the same type of experiment tasks presented in [83], Riecke *et al.* [77] demonstrated the opposite results compared with the results of Ruddle *et al.* [83, 84] that showed that *BodyTrans* rather than *BodyTurn* is necessary for establishing effective cognitive map in terms of direction and distance estimates. Ruddle *et al.* used search tasks in small [83, 84] and large-scale [85, 86] environments, and showed the consistent results from a series of these studies.

Thus, due to the incompatible results between Riecke *et al.* [77] and Ruddle *et al.* [83, 84] on the effectiveness of *BodyTurn* to acquire spatial knowledge, it is not clear yet whether *BodyTurn* is effective in spatial knowledge acquisition. Moreover, no study has been attempted to demonstrate the effect of *BodyTurn* by evaluating two types of spatial knowledge, i.e., route and survey knowledge, separately. Although the cognitive map includes both aspects of route and survey knowledge and the search task would be a good evaluation task to measure the cognitive map, it is not clear that what type of spatial knowledge (route or survey) more dominantly affected the results of the studies. In the studies of both Riecke *et al.* [77] and Ruddle *et al.* [83, 84, 85, 86], if route knowledge and survey knowledge were separately evaluated, there could be different conclusions.

Hence, it would be worth to investigate the effect of *BodyTurn* on route and survey knowledge separately because no research has separately demonstrated it for route knowledge and survey

knowledge. We believe that *BodyTurn* without cyclic leg-movement should show some effects in spatial knowledge acquisition if *action* plays a central role for spatial knowledge acquisition as we understood about humans' spatial learning in §3.1. The design and implementation of *body-turn based* approach and its effect on spatial knowledge acquisition are presented in Chapter 4.

3.2.2 Action Transferred Approach: From Feet to Fingers

Even though the body-turn based approach can resolve the issues, e.g., large-controlled-space, specialized system configurations and whole-body fatigue, of walking-like NavTechs, the body-turn based approach cannot be used conveniently as much as non-body-control-based NavTechs because the body-turn based approach still needs the whole-body-turn. Hence, there can be still the design trade-offs between effectiveness and convenience for designing effective and convenient NavTechs in spatial knowledge acquisition.

We recognized the value of the motor equivalence theory in §3.1.4. Rather than using an *action* “as it is”, the design trade-offs can be resolved by transferring the action to other biological effectors of smaller muscle groups, so that the *action* can be more conveniently performed. That said, if the action, tightly coupled with perception for spatial learning, can be performed by the other biological effectors as well as the original effector(s), there can be a possibility to design NavTechs not only for effective spatial knowledge acquisition but also for convenient use in VEs. Walking is dominantly executed by the lower limbs although it is whole-body movement. If we transfer the action of walking to the upper limbs, such as two arms, two hands or two fingers, we can perform the action more conveniently (without whole-body movement), compared to using the original effectors.

Thus, using the motor equivalence theory (specifically, using the concept of transferred action) is a plausible approach to design of convenient and effective NavTechs for spatial knowledge acquisition, resolving the design-tradeoffs (§1.1). How can we apply this concept to designing a new NavTech? The logical way would be first to find the abstract form that is encoded in our brain,

which is actually transferred to the other body parts. However, the abstract form can be only conjectured from the original action as shown in [81] where ‘Zigzagging’ motor pattern² was assumed as an abstract form of ‘signing’ action. Hence, we attempt to mimic “walking action” by fingers because there is an intuition that “finger-walking” or using two fingers to simulate bipedal walking is a common human experience. From childhood, “finger-walking” is used both for play and for illustrating walking action.

As a common human experience, “finger-walking” has a similar form of a gait cycle [82] of walking. The simple form of the gait cycle is comprised of stance and swing phases [82]. Based on this gait cycle, “finger-walking” can mimic some variations of walking, e.g., walking straight or diagonally forward, walking straight or diagonally backward, walking sideways, and turning in place. The cyclic form of stance and swing phases can be seen in these mimicked variations of walking. This cyclic stance and swing form may be considered as an abstract form of walking in terms of the concept of transferred action. Although bipedal walking can be mimicked by any pair of two effectors, such as two arms, two elbows, two hands or two fingers, two fingers are chosen because using fingers can reduce any greater body fatigue and provide finer control than the other effectors [124], as well as the common intuition of “finger-walking”.

It is noted that this “finger-walking” is not performed with the same intention (or goal) of walking in the real world. However, ‘walking’ and “finger-walking” can have the same goal in virtual worlds. Suppose that the intention (or goal) of walking is to move or navigate to acquire spatial knowledge in virtual space. In order to achieve the goal, one needs not to physically move around, but only perform the walking action that can be detected by VE systems, and consequently the walking action is used to navigate the virtual space. From this point of view, one can achieve the same goal with “finger-walking” in VEs as long as VE systems can detect the movement of “finger-walking” for updating the virtual scenes correspondingly. Thus, “finger-walking” can be performed with the same goal of walking for navigation in VEs.

²It should be noticed that ‘zigzagging’ action itself is not the same action of ‘signing’ unless the zigzagging action has the same ‘intention’ or ‘goal’ as the signing action.

We present the details of design and implementation of an action-transferred NavTech based on “finger-walking” , and demonstrate its effect on spatial knowledge acquisition in Chapter 5.

3.3 Chapter Summary

We provided our theoretical reasoning related to action, perception, and learning. We observed that the core-elements of spatial learning are *action* and *perception*, but not necessarily body parts. This observation was also supported by the motor equivalence theory. We focused more on *action* rather than *perception* to propose our new design approach. We proposed two types of action-inspired approach, *body-turn based* and *action-transferred* approaches.

Although *body-turn based* approach was not new, no study has attempted to investigate the effect of *body-turn* on route and survey knowledge acquisition separately. Hence, it would be worth to investigate the effect of *BodyTurn* on route and survey knowledge separately. We believe that *BodyTurn* without cyclic leg-movement should show some effects in spatial knowledge acquisition if *action* plays a central role for spatial knowledge acquisition as we understood about humans’ spatial learning in §3.1. We will present the design and implementation of a body-turn based NavTech, and demonstrate its effect on route and survey knowledge acquisition in Chapter 4.

On the other hand, our action-transferred approach is newly proposed in this dissertation as no previous research has attempted. Although the motor equivalence theory (specifically, the concept of “action-transfer”) has been proved in various research areas [27, 41] including neuroscience and neurophysiology using fMRI [81, 98], applications and implications of the theory have not been investigated in designing interaction techniques including NavTechs. We believe that we are the first contributors to recognizing the value of the theory and to adopting the theory to design effective NavTechs. We will demonstrate the effectiveness of this action-transferred approach using the “finger-walking” based NavTech, the design and implementation of which are detailed in Chapter 5.

Chapter 4

Design and Evaluation of Body-Turn Based Approach

We proposed a body-turn based approach as one of action-inspired approaches to designing effective navigation techniques (NavTechs) for spatial knowledge acquisition in the previous chapter (§3.2.1). In this chapter, we present our design of a NavTech using the body-turn based approach, i.e., body-turn based NavTech, and describe how to evaluate the approach using the NavTech through a comparative user study in a large-scale, large-extent and visually impoverished virtual space using a CAVE virtual environment system.

Most environments used in studies involving human navigation can be classified as a combination of three aspects, scale, extent, and visual-richness, of an environment. In a large-scale environment, people cannot grasp spatial information of the environment from a single viewpoint and must explore the environment to integrate spatial knowledge from separate viewpoints and navigational experiences. On the other hand, navigation is not necessary in a small-scale environment which has no visual barrier through a single viewpoint unless the objective of navigation is to precisely observe objects in the environment, focusing on size or shape. Extent refers to the spatial size of an environment as described in [86]. If an environment is large-extent, then it is usually large-scale. However, there are some exceptions, such as office place with tall partitions (large-scale but

small-extent) or open-park (large-extent but small-scale). Although space is relatively determined as large extent or small extent, we defined large-extent space as the place's size is approximately larger than several thousands square meters in this dissertation. Hence, people need to spend some time (a few minutes) to move around the whole area of large-extent space.

Based on visual richness of an environment, there can be visually rich or visually impoverished environment. Although it is hard to quantifiably distinguish between visually rich space and impoverished environment, we defined visually rich environment as the environment with natural and rich visual cues where we normally experience in our day to day interaction with the environment – *ecological environment*. On the contrary, there are environments with a lot less visual information such as maze or desert, which we refer to visually impoverished space in this dissertation.

If visually rich-cues are used, those visual cues can more dominantly affect human's spatial cognition [79, 78]. We assumed that some visual cues influenced on human's spatial cognition would not be coupled with the 'walking' action. Hence, we tried to minimize the types as well as the amount of visual cues in our test VE so that our investigation can be more focused on the comparison of different types of action performed by NavTechs.

Our evaluation focused on measuring the accuracy of both types of spatial knowledge, i.e., route and survey knowledge. For this purpose, we provide "route-replication" task for assessing acquired route knowledge, and "map-based multiple choice" and "direction-estimates to targets" tasks for assessing survey knowledge in a large-scale and large-extent space. With less visual information, navigating large-scale and large-extent space should place a lot of cognitive loads on participants to complete the tasks as we assume. Consequently the measured data would not reflect any "ceiling effect" which refers to no difference between participants in performance when the given task is too easy to perform.

A large-scale, large-extent and visually impoverished space is unlike an ecological environment. However, there can be real situations quite often happened, which may not provide rich visual information. For example, military training may require soldiers to explore large abandoned buildings or deserted areas. Firefighter training can be carried in burned buildings that only have layout

but no signs. Some environmental features could be hidden by fire and smoke. Another important application of VEs is large-scale disaster rescue training, such as earthquake or mine collapse, where far less visual information is available. Hence, our comparative study can contribute to these VE applications by examining how effectively action-based NavTechs can support spatial knowledge acquisition in a large-scale, large-extent and visually impoverished space.

For our comparative study, we provided two other NavTechs to be compared with our body-turn based NavTech. The first one is a wand and joystick based common NavTech (*JS*) in virtual environments (VEs). The *JS* is selected as a non-walking common NavTech to be compared with our body-turn based NavTech because the *JS* is commonly used in many VE applications although the *JS* allows body-based physical movement (i.e., body-turn and walking around) in a physical VE space. The second one to be compared with our body-turn based NavTech is a walking-like NavTech, providing both body-controlled translation and rotation. For this comparison, we provided our own walking-in-place (WIP), named *Sensor-Fusion Walking-in-Place (SF-WIP)*. We describe the design, implementation and validity test of *SF-WIP*, and then present our evaluation of our body-turn based approach. Thus, our comparative study is performed focusing on two comparisons, (1) body-turn versus non-body-controlled (*JS*) and (2) body-turn versus body-controlled translation and rotation (*SF-WIP*).

4.1 Body-Turn Based Navigation Technique: JS_m

In order to design a body-turn based NavTech, we simply replaced rotational control of the *JS* (§4.2.1) with body-turn (or you can replace translational control of walking-like NavTechs with that of the *JS*), resulting that the joystick-controlled orientation of *JS* was disabled while the wand's orientation is used to control virtual orientation. In order to obtain the wand's orientation for our body-turn based NavTech, we used a customized fixture (made of plastic) with a belt (Figure 4.1) so that the wand device was attached on a participant's body, resulting in forcing the participant to make body-turn for orientation control. In this condition, the joystick was used only for transla-

tional control. The third and fourth buttons on the wand were used to control the maximum speed of virtual movement (Figure 4.1). Thus, our body-turn based NavTech can be easily designed by modifying JS, as named JS_m in this dissertation.

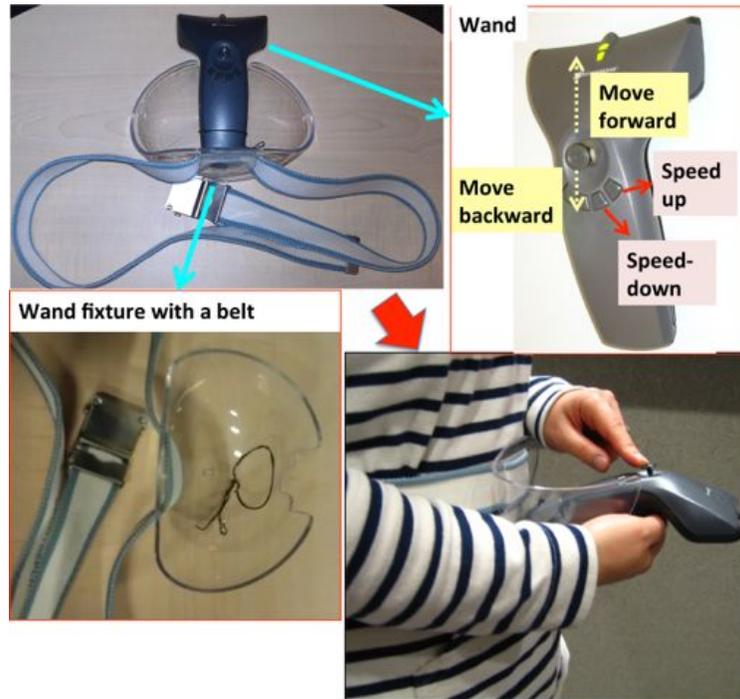


Figure 4.1: Body-turn based NavTech (JS_m).

4.2 Compared Navigation Techniques

In this section, we described two NavTechs to be compared with our body-turn based NavTech (JS_m).

4.2.1 Wand and Joystick Based NavTech: JS

A wand and joystick based NavTech (JS) as shown in Figure 4.2 is very commonly used in VEs due to its convenience. We used the wand device which has a two-degrees-of-freedom (DOF)

joystick and four buttons on the top. For our comparative study, we assigned some functions to the four buttons. The first and second buttons were used to control the maximum speed of virtual rotation down and up, respectively. The third and fourth buttons were used to control the maximum speed of virtual translation down and up, respectively. The displacement of the joystick controls the rate-based speed for both translation and rotation.

In the JS, the pointing direction of the wand indicates the heading direction (i.e., yaw) of the user’s navigation. Also, the user was only allowed to virtually move on a 2-dimensional (2D) horizontal plane in our test VE. The joystick on the wand was used for both translation and rotation of the user’s viewpoint in a 2D plane. Any control for pitch and roll rotations, and up and down translations was disabled in our test VE. Participants were allowed to physically turn or move the body. Thus, the JS can provide a confound orientation control, i.e., body-turn based and joystick-based.

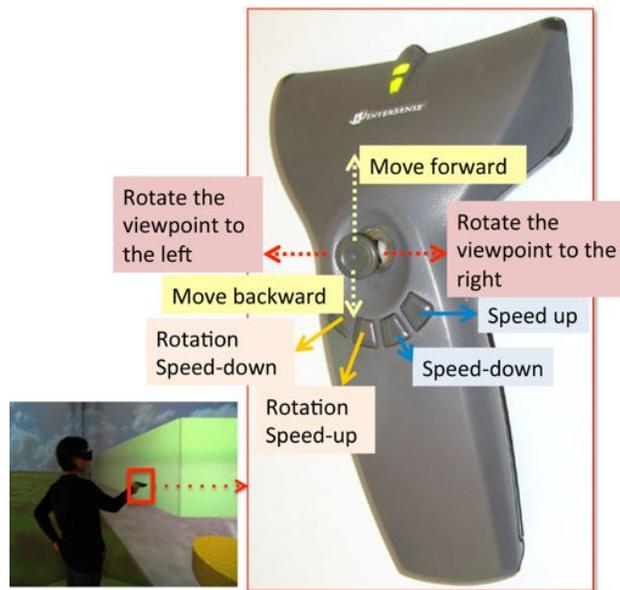


Figure 4.2: Wand device with a little joystick and four buttons for the common NavTech (JS).

4.2.2 Walking in Place NavTech

In order to compare the effect of body-turn on spatial knowledge acquisition with a walking-like NavTech, we needed to provide a walking-like NavTech. There can be several types of walking-like NavTechs, such as natural walking, treadmill-based walking, or walking-in-place NavTechs (§2.2.1). However, the treadmill-based approaches require expensive and/or obtrusive additional equipment. The existing walking-in-place (WIP) NavTechs are mostly based on a wired communication between their in-house devices and a server (computer). Dealing with wires or tangled cables introduces some movement constraints that may result in lowering users' task performance [10, 119]. In addition, the WIP NavTechs have some start-stop latency issues [25, 113] due to the characteristics of the detection algorithm for walking (gait) movement. In order to minimize the possible issues, we decided to newly design our own WIP NavTech, named *Sensor-Fusion Walking-in-Place (SF-WIP)*.

4.3 Sensor-Fusion Walking in Place NavTech: *SF-WIP*

The sensor-fusion walking in place NavTech (SF-WIP) was designed to satisfy three goals (1) *untethered (wire-free) interface*, (2) *dynamic walking-speed change* and (3) *easy implementation and replication* so that it can be used as a walking-like NavTech by minimizing the issues (§4.2.2) of existing WIP NavTechs for our comparative study.

We employed smartphones for the goals. The current generation of smartphones is equipped with a variety of sensors detecting acceleration, magnetic field strength, screen touch, rotation, and presence of nearby objects in order to improve users' experiences. In addition, smartphones provide multiple wireless data communication standards, such as WiFi and Bluetooth, along with software-development libraries. For this dissertation, we used Android smartphones (200g per each).

Our design for the SF-WIP started by understanding the performance of a single sensor-based WIP through careful observation. Acceleration, magnetic flux density, and rotation sensors can be

useful to track the human walking. Rotation sensor (gyroscope) may provide more precise data, but requires more complicated computations [117]. Since we adopted the smartphones having lower computing power than a desktop computer, we excluded the rotation sensor for our design. Thus, our observation was focused on the performance of two types of sensor, acceleration and magnetic sensors.

4.3.1 Magnetic Sensor Based Walking in Place

The magnetic sensor embedded in smartphones generally detects the magnetic flux density of the Earth. We used a rare earth magnet (231N pull force; $5\text{cm} \times 1.27\text{cm} \times 1.27\text{cm}$) to override Earth's magnetic field. Thus, detected strength of the magnetic flux density can vary with distance between the magnet and the sensor, and with their moving speed. After several trials of positioning the magnet and a smartphone on the body, we arranged the location and orientation of the phone and the magnet to obtain strong signal variation detected for human walking (Figure 4.3a).

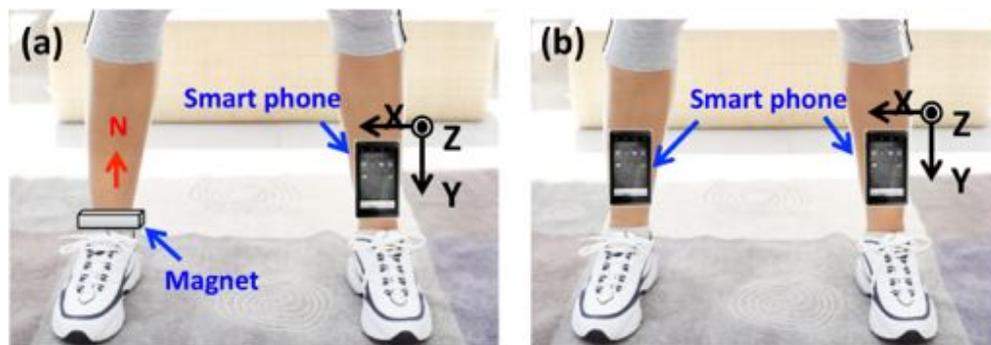


Figure 4.3: (a) Magnet sensor-based walking-in-place and. (b) Acceleration sensor-based walking-in-place [46]. Copyright ©2012 IEEE

With this configuration shown in Figure 4.3a, the measured magnetic-flux-density amplitude on each leg during walking in place in x , y , and z directions is depicted in Figure 4.4a. The second time derivative of the magnetic sensor data can be viewed as the acceleration of the magnetic-flux-density change. Thus, it is effective to detect the intended speed change during human walking. For example, the discrete second time derivative of the measured magnetic data in the y -direction

is shown in Figure 4.4b where the detected points beyond an empirically-determined threshold value are marked. The detected points can be used for virtual movement. Whenever a point is detected during walking, virtual movement can be obtained by an empirically determined scale value. We assume that the number of detected points per step can be increased as the legs move faster, so that the virtual movement can be correspondingly faster. Unfortunately, for fast stepping (or walking), the variation of the magnetic flux density over time was too high to be measured by the magnetic sensor of the test smartphone, so the sensor did not work properly during fast stepping (Figure 4.4a).

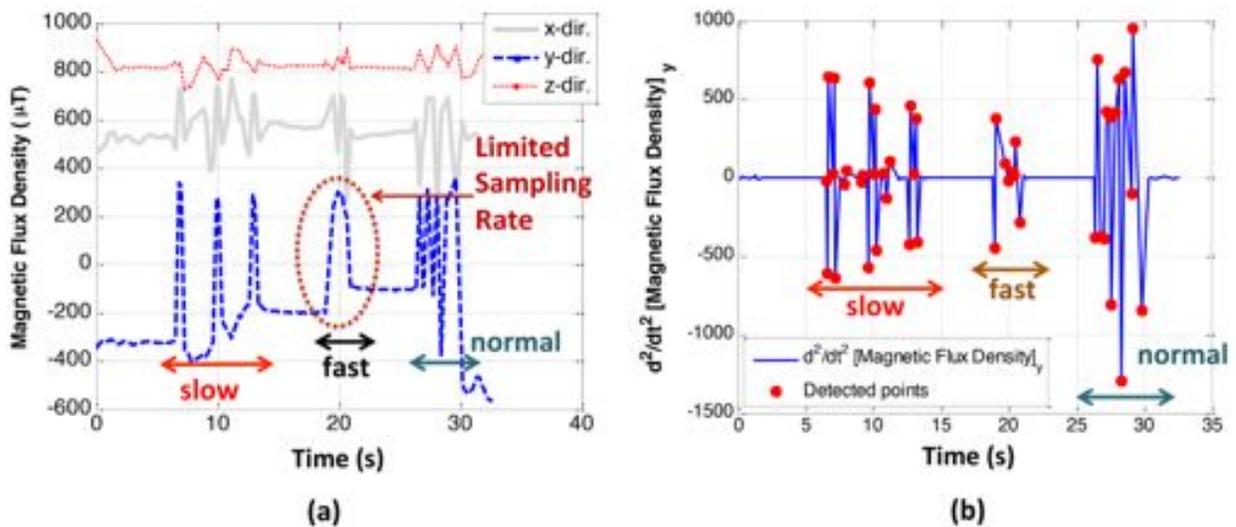


Figure 4.4: Data of magnetic sensor: (a) Measured raw data of magnetic sensor in three directions for 30 steps (Gray solid line: x -direction; Blue dotted line: y -direction; Red dotted line: z -direction) and (b) Second time derivative of the magnetic flux density in y -direction for 30 steps [46]. Copyright ©2012 IEEE

4.3.2 Acceleration Sensor Based Walking in Place

We used two smartphones attached to both ankles (Figure 4.3b) to detect stepping of both legs. The measured acceleration sensor data on each leg during walking in place in x , y , and z directions are depicted in Figure 4.5a. The measured data on two legs were similar to each other. The y -direction acceleration data shows the strongest amplitude response, which can be more useful to

detect human walking than the data in the other directions.

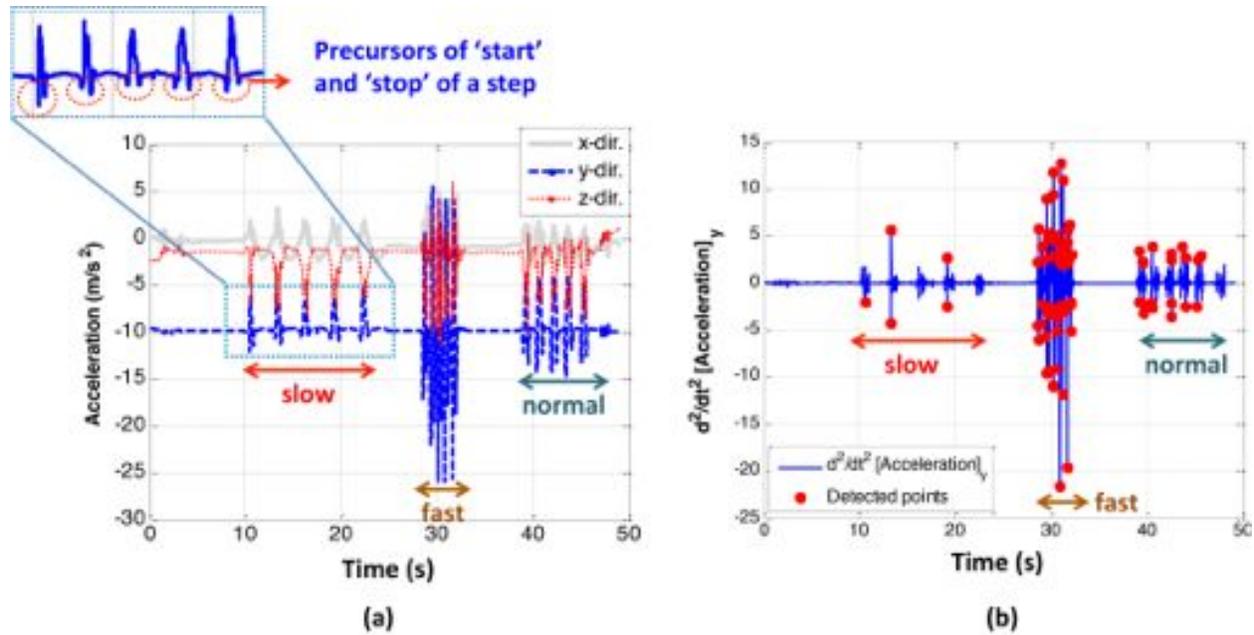


Figure 4.5: Data of acceleration sensor: (a) Measured raw data of the accelerometer in three directions for 15 steps (30 steps per two feet) (Gray solid line: x -direction; Blue dotted line: y -direction; Red dotted line: z -direction); (b) Second time derivative of the acceleration in y -direction for 15 steps (30 steps per two feet) [46]. Copyright ©2012 IEEE

By observing the raw data in the y -direction, we found a small and fast accelerated fluctuation right before the step started and after the step ended. This phenomenon can be understood by the Newton's third law of motion between the foot and the ground. In other words, if a person provides a force to the ground, then the ground pushes the foot back. During this moment, the foot is still on the ground, but the small movement can be observed from the measured acceleration data as shown on the top-left in Figure 4.5a. We call them *precursors* that can be used to reduce the start-stop latency, if these are detectable. In the present setup using smartphones, we found that these precursors are not always detected due to the limitation of the accelerometer's sampling rate. It can be an interesting future work to use the precursors to reduce the well-known start-stop latency of previously-developed WIP NavTechs using high-end sensors.

The acceleration changes very rapidly (Figure 4.5a). Thus, higher-order derivative of the ac-

celeration sensor data can be useful to detect the human walking with the accelerometer. The acceleration-sensor-based approach using the detected points from a second time derivative of acceleration in physics) can support normal and fast walking (Figure 4.5b), while the magnetic sensor based approach does not support normal or fast walking.

4.3.3 Implementation of SF-WIP

As observed in the data of magnetic and the acceleration sensors, each sensor's detection range of walking speed can be limited, depending on the change of intended walking speed. We decided to combine two single-sensor-based WIP NavTechs, which leads us to a sensor-fusion approach. Two smartphones and one magnet were properly re-positioned as shown in Figure 4.6. If both the magnet and the smartphone are attached to the front side of an ankle, the phone's magnetic sensor can be overloaded with a strong magnet field.

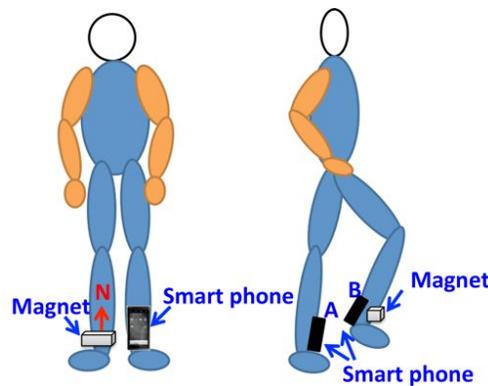


Figure 4.6: Arrangement of a magnet and two smartphones for sensor fusion approach. smartphone A detects both acceleration and magnetic density field and acceleration of walking. smartphone B only detects acceleration of walking.

Our sensor-fusion approach is a linear combination of two single-sensor-based WIP NavTechs described in §4.3.1 and §4.3.2. Our current algorithm is illustrated in Figure 4.7. Since our algorithm simply uses the discrete second time derivative of each sensor data for human walking detection, we only need the previous and the current sensor data in essence, resulting in low computation

overhead. In other words, the proposed algorithm does not require the data accumulated during a gait-cycle (or half gait-cycle) or any gait model to update the virtual movement speed, which is usually required by other filtering algorithms. Consequently, its detection capability is not noticeably affected from wireless communication data loss. The threshold values (i.e., M_{th} and A_{th} in Figure 4.7) for each sensor can be empirically determined. For our initial evaluation, we found 2 and 15 as the threshold values for acceleration and magnetic sensors respectively.

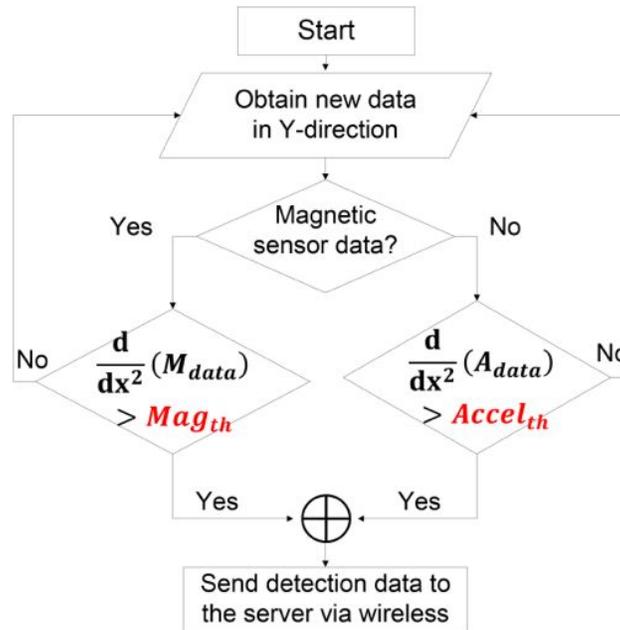


Figure 4.7: Human walking detection algorithm (sensor-fusion) [46]. Copyright ©2012 IEEE

The essential implementation for virtual movement is based on Equation 4.1:

$$\begin{aligned}
 \text{Virtualmovement} &= \text{detected value} * \text{scale value} \\
 \text{scale value} &= \text{individual's stride length}/8
 \end{aligned}
 \tag{4.1}$$

The *detected value* (or *point*) is either $d^2/dt^2(M_{data}) > M_{th}$ or $d^2/dt^2(A_{data}) > A_{th}$. M_{data} is magnetic flux density, M_{th} is magnetic flux threshold, A_{data} is raw acceleration data, and A_{th} is acceleration threshold. The *scale value* can be obtained by a calibration process for individuals.

Based on our unofficial pilot study, we found that users did not feel any jumpy movement when the number of the detected points in the SF-WIP is over seven or eight points per step at their normal walking speed. We provided a calibration tool to find the scale value specific to individuals. We first asked each user to walk five steps four times on the physical ground and used the average as the stride length. We then asked the user to put on two smartphones and a magnet and walk in place for ten steps at her/his normal speed. Our calibration tool calculates the optimal scale value for the user by using the stride length and the number of detected points (i.e., 8 in this dissertation). The optimal number of detected points can be differently determined by some factors, such as different smartphones.

A *counter number* is used because there is a possibility of data loss over UDP communication. The *counter number* is the number of data sent (phone) subtracted by the number of data received (server) + 1 (default value). If the number of data sent is greater than or equal to the number of data received, then the virtual movement is updated as time(s) as the *counter number*.

4.3.4 Challenge of Wireless Communication

In a typical cluttered laboratory environment, the data transmission speeds on wireless links can be much slower than the sensor-data sampling rate due to severe signal fading and interfering issues [72].

The result of the ping test in our laboratory environment showed very inconsistent communication speed of the range from a couple of ten milliseconds to a few hundred milliseconds, depending on when it was measured. If human walking detection algorithm is not versatile to the random delay and the change of effective sensor sampling rate, users can have trouble in navigation.

We tried to address this issue by changing TCP-based to UDP-based communication, resulting that we were able to reduce the time for congestion control and for sending acknowledge-packets. The data packet (2-byte as the minimum size) transmitted to the Linux server (than runs our VE system) essentially includes the counter number of the current detection as well as the detection

value during walking (or gait) movement. Thus, some data loss due to UDP communication and network delay could be tolerated. Table 4.1 shows the data transmission speed over wireless link and sensor sampling rate in our setup.

Table 4.1: Wireless transmission speeds and sensor sampling rates of the smartphones used in this dissertation.

	TCP Speed	UDP Speed	Acceleration sensor rate	Magnetic sensor rate
Range	10–1000 ms	2–100ms	40-45Hz	7–10Hz

4.3.5 Validity Test of SF-WIP

The main goal of this validity test was to verify that our sensor-fusion approach can overcome the drawback of a single-sensor based approach, i.e., the limit of the dynamic change of walking speed. We performed an informal pilot study with a couple of users. We compared three types of sensor-based approach, i.e., acceleration sensor, magnetic sensor, and sensor-fusion, for evaluating their performance in a simple navigation task with three predefined speed parameters. It was assumed that there was a smooth and continuous speed transition between different speeds.

Apparatus: We used a Linux-based cave automatic virtual environment (better known by the recursive acronym CAVE) [105], which is an immersive VE system, including three 10' by 10' walls and a floor stereo projection screens, each with 1920×1920 resolution and 60 Hz refresh rate, and an Intersense IS-900 VET tracking system (120 Hz update) for a head tracker, attached on the shutter glasses. We used a wireless wand tracking device fixed on an empty backpack to determine the user's body orientation. This fixation remained in place even when the user ran in place. The user's hands were free with our SF-WIP (Figure 4.8). Thus, our SF-WIP NavTech with a full wireless configuration minimized possible constraints on the user's movements when performing the navigation tasks.

Design of virtual space: Figure 4.9 shows the top view of the virtual world (obtained from Google 3D warehouse) where a street is in the middle, the buildings are on the left side, and a small park

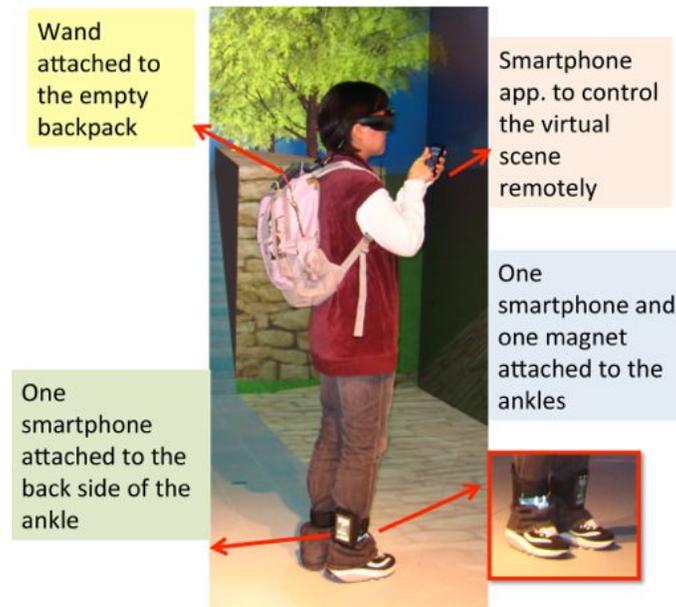


Figure 4.8: Sensor-fusion walking in place (SF-WIP) NavTech in CAVE.

is on the right side. Five poles per speed-section, in the order of yellow, blue and red ones, are placed to present different-speed-sections on the street. There is a spatial interval of two *meters* between two poles. We selected three pre-defined stepping frequencies, 0.75, 1.5, and 2.8 Hz that correspond to a slow, normal and fast walking speeds respectively. The use of predefined stepping frequencies helped us clearly observe the differences between three types of sensor-based approach. Each user practiced stepping-in-place with a metronome beat for three frequencies.

Procedure: Each user walked on the street at each of the three speeds by following the yellow, blue and red poles. If any WIP NavTech using acceleration sensor, magnetic sensor or sensor-fusion does not support the dynamic change of walking speed, the user cannot pass all the poles on the street. The time allocated to each test in three types of WIP NavTechs was 1 minute.

Results: Figure 4.10 shows the test results for each type of sensor-based WIP. Using the acceleration-based WIP (Figure 4.10a), the user was not able to pass the slow speed section (yellow poles) because the number of the detected points decreased and became zero at some point. This indicates that the simple acceleration-based WIP cannot support slow-speed walking well. The user easily moved forward at the slow speed with the magnetic-sensor-based WIP (Figure 4.10b), but

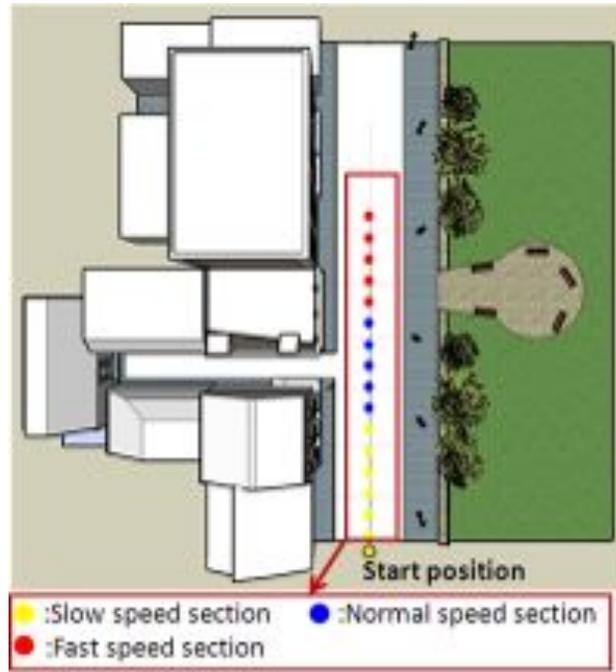


Figure 4.9: Top view of the virtual world used for evaluation. A user walks following the yellow, blue, and red poles with different speeds.

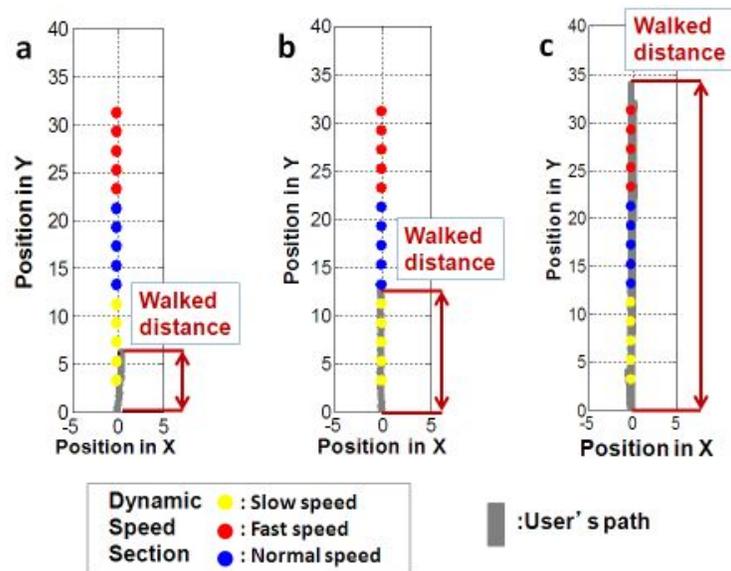


Figure 4.10: The results of three types of sensor-based WIP NavTechs. (a) The accelerometer based WIP. (b) The magnetometer based WIP. (c) Sensor-fusion WIP (SF-WIP) [46]. Copyright ©2012 IEEE

not at the normal or fast speeds since the number of the detected points of the magnetic sensor data decreased as the walking speed increased. The magnetic-sensor-based WIP cannot support both normal and fast walking-speeds well. Figure 4.10c shows that the user completed three different speed-sections with successful continuous transition between different speeds when using our SF-WIP. Thus, our validity test supports that our sensor-fusion approach works well for the dynamic speed range from very slow (0.75 Hz) to very fast walking speed (2.8 Hz).

4.4 Evaluation: Body-Turn Based NavTech

For this evaluation, we hypothesized that the JS_m (body-turn based NavTech) would be more effective than the JS (non-walking and common NavTech) on spatial knowledge acquisition while the SF-WIP (a walking-like NavTech) would be more effective than the JS_m on spatial knowledge acquisition because body-turn in JS_m is a partial action of walking-like NavTech. Or, the SF-WIP and the JS_m would have equal effect on spatial knowledge acquisition if body-turn (as a common movement in two NavTechs) more dominantly affects spatial knowledge acquisition than other movements of walking action.

We used a between-participants design with three NavTech groups to test our hypothesis. The objective was to investigate the effect of the JS_m technique on spatial knowledge acquisition, specifically route and survey knowledge acquisition separately, compared to the JS (wand and joystick based NavTech) and the SF-WIP (a walking-in-place NavTech) in VEs. Hence, our investigation was focused on two comparison, (a) JS_m versus JS and (b) JS_m and $SF-WIP$ on route and survey knowledge acquisition.

In addition we decided to examine the subjective sense of presence of participants. According to [104], walking-like NavTechs (e.g., real walking and walking-in-place) significantly enhanced the subjective rating of presence compared to a wand-and-joystick common NavTech. We wondered whether the subjective sense of presence is also enhanced by the body-turn NavTech (JS_m) without cyclic leg-movement as much as the original action based NavTech (i.e., SF-WIP).

4.4.1 Method

Virtual Environment System

We used a Linux-based CAVE [105] system including three 10' by 10' walls and a floor stereo projection screens, each with 1920×1920 resolution, and the Intersense IS-900 VET tracking system for a head tracker, attached on the shutter glasses. The display refresh rate is 60Hz. Since this tracking system is provided by a dedicated wireless infrastructure, the refresh rate of the tracking system is constant (120Hz).

The virtual space and objects were modeled with Google SketchUP and imported into the OpenSceneGraph and DIVERSE [40] software framework. In order to facilitate the experiment with several tasks, we also implemented a remote control application on an Android smartphone. Hence, one experimenter was allowed to control the experiment tasks or reset the scene while she/he was giving some instructions to participants in a training phase and a testing phase. In addition, the experimenter was allowed to observe each participant's behavior during the entire experiment without any interruption.

Design of Virtual Space

We used a single virtual space (maze) for both route and survey knowledge acquisition in our experiment so that participants were allowed to extensively explore the entire maze and gain navigational experience. This extensive navigational experience should help the participants to establish multiple relationships between various locations to construct map-like representation of the entire maze (i.e., survey knowledge).

Figure 4.11a shows the virtual maze, which is designed with large-scale, large-extent [86] and less visual information. The irregular structure of the maze's layout would provide more complicated spatial navigation to the participants. There are three routes from the entrance to the exit. In our informal pilot study we observed that participants got cyber-sickness even for a short period of

navigation in the narrow corridors with the texture-based walls. Hence, we decided to have a solid green color walls without any texture to reduce the occurrences of cyber-sickness (Figures 4.11b and 4.11c).

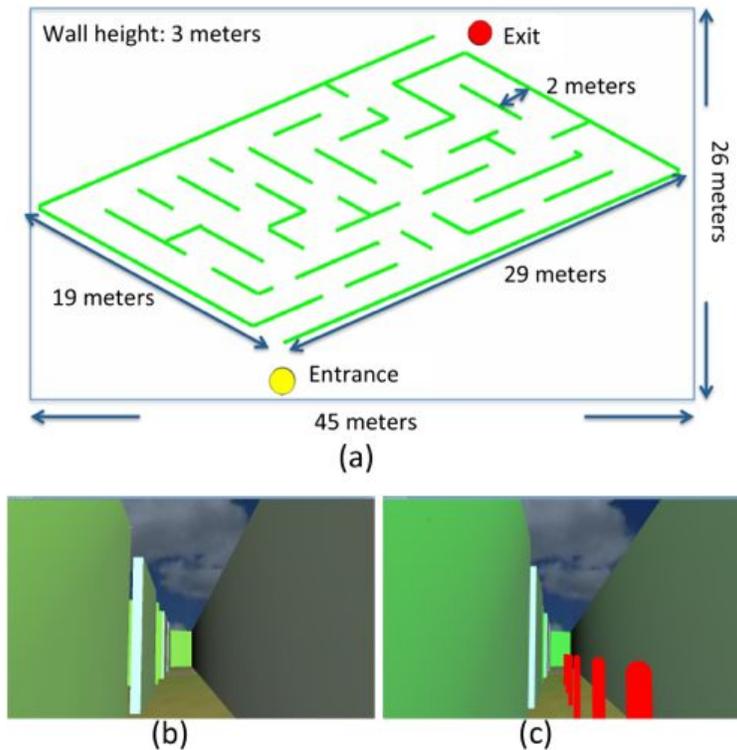


Figure 4.11: (a) Virtual maze layout (b) first-person view without waypoints (c) first-person view with waypoints.

Because our CAVE system has an open back wall (i.e., no projection), the participants using the JS_m and the SF-WIP can face the open back wall when they physically turn. This turning in place to the open back wall can have *dual-role*, as a landmark or a visual barrier [42]. In order to provide compatible conditions for all three NavTech groups, the participants with the JS had a virtual black wall [42]. We provided a diamond shaped maze (Figure 4.11a) so that the participants using the JS_m and the SF-WIP can minimize the chances of facing the open back wall during navigation. In our informal pilot study, we actually attempted to use a head-mounted display (HMD) to resolve this open back wall issue of the CAVE system. However, we observed that the heavier weight of the HMD than the stereoscopic glasses in CAVE, could more significantly affect the participants' task

performance (the same issue was reported in [88]) because they had to perform virtual navigation by turning the head a lot of times for one hour including training sessions. Especially our maze environment without any salient landmark would require the participants to move the head more frequently to rely on spatial layout for wayfinding.

Three pre-defined routes from the entrance to the exit were provided. They were marked by red (Figure 4.12a), blue (Figure 4.12b) and yellow (Figure 4.12c) waypoints. These waypoints were used to provide participants with visible pre-defined routes. In order to facilitate participants' route replication tasks as well as measure the orientation estimate of the participants, two landmarks were placed on each route in the maze. The path length of the red, blue, and yellow routes through the waypoints is approximately 50, 70 and 64 meters, respectively.

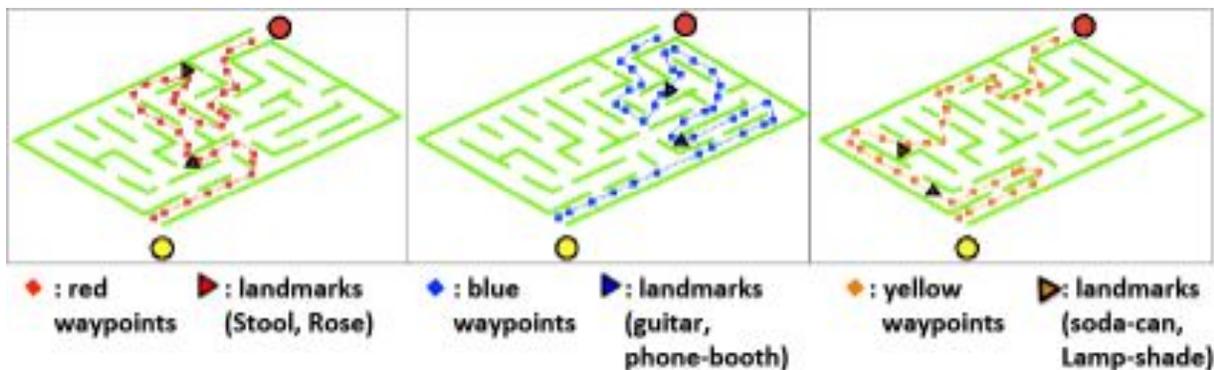


Figure 4.12: Three views for three reference paths (red, blue, and yellow) from the entrance to the exit. A diamond mark indicates the position of waypoint. The black triangle marks in the maze indicate landmarks; two landmarks used for each reference path.

Pre-Experiment Spatial Ability Test

We used the test of self-report sense of direction (SOD) [33] which all participants took at the beginning, in order to evenly distribute the participants into three NavTech groups. The SOD test consisted of 27 items scored on 7-point Likert-scale, so that we were able to instantly assign the participants to the NavTech groups.

All participants also took Perspective Taking Spatial Orientation Test (PTSOT) [34] after the SOD test. The PTSOT consists of a 2D array of objects that are shown to the participants. The participants indicate (from their imagined perspective) the direction to a target by drawing an arrow. A participant's score is the average deviation across all items. However, if no answer was provided, a score of 90 per question was assigned. Since obtaining the average score of PTSOT (12 questions in total) from a participant takes more time than the SOD, the results of PTSOT were used to confirm whether the distribution of participants was spatial-ability-balanced across three NavTech groups.

Participants

We recruited participants with no disability from on-campus listserv and a participant recruiting system maintained by our school. All participants gave a written informed consent for the study. Twenty participants per group were expected. However, eight participants withdrew because of severe cyber-sickness, seven (5 female) from JS group and one (female) from SF-WIP group. No one withdrew from the JS_m group. Hence, we recruited additional participants so that we were able to collect the data of twenty participants per group, who completed the experiment tasks.

The sixty participants were randomly assigned to three groups, being spatial ability balanced. An analysis of variance (ANOVA) for SOD and PTSOT results did not show any significant difference between three groups; SOD: $F(2, 59) = 0.00$, $p \geq .997$; PTSOT: $F(2, 59) = .53$, $p = .592$. JS and SF-WIP were gender-balanced (10 male and 10 female per group), but JS_m group was not (11 male and 9 female).

Each participant took approximately 90 minutes to complete the experiment, including taking short breaks and responding to the pre-/post-experiment questionnaire. Undergraduate students (nineteen participants per group) were compensated with two course credits. Graduate students (one participant per group) were not compensated and only voluntarily participated. The other demographic data are summarized in Table 4.2.

Table 4.2: Summary of demographic data of participants.

NavTechs	Age	# of users with VEs experience	# of players of video games
JS	$M = 20.05, SD = 1.395$	Female:1, Male:3	Female:7, Male:10
JS_m	$M = 20.15, SD = 1.932$	Female:2, Male:2	Female:4, Male:11
SF-WIP	$M = 20.15, SD = 1.663$	Female:0, Male:2	Female:4, Male:9

Procedure

The study was designed with two training sessions and one test session. The first training session helped the participants to get familiarized with a given NavTech and virtual navigation in an open virtual space (a public park with some benches and walking trails). The second training session was designed for the participants to get familiarized with navigating a virtual maze that is similarly designed as the test virtual maze but with less complexity. The participants were informed and trained about the dual-role of the open back wall (for the JS_m and SF-WIP NavTechs) and the virtual black wall [42] (for the JS NavTech). The initial speed of virtual movement was between 1.2 m/s and 1.6 m/s . All participants were allowed to change their movement speed. The range of movement speed is from 0 m/s to 10 m/s with the JS and the JS_m NavTechs, but the maximum speed of the SF-WIP cannot be determined because it depends on the speed and the frequencies of leg-movement of the participants. All participants were informed that it is important to move around virtual space at their comfortable speed, resulting that the virtual navigation speed of the participants quite varied. Even within a participant, dynamic speed changes were observed due to slow-stepping, fast-stepping (or running in place), small-amount of leg-movement, or large-amount of leg-movement. The two training sessions lasted about 20 minutes, including the instructions and the participant's inquiries (if any). The participants were asked whether they clearly understood how to use the given interface and how to navigate the virtual maze. If not, they were allowed to have more practice time with the given NavTech in the virtual maze.

The test session consisted of four sub-sessions and approximately lasted 40 minutes in total. For

the first three sub-sessions, the participants learned three different pre-defined routes from the entrance to the exit. A route replication task was performed at the end of each sub-session. In the last sub-session the participants freely explored the maze to familiarize with the entire area and the layout of the maze. The main tasks performed during the experiment include:

1. *Route replication per sub-session* This task was designed to measure the accuracy of the participant's route knowledge during the first sub-session and provide the participants with extensive experiences in the maze during the next two sub-sessions. At first, each participant followed the waypoints on the pre-defined route until she/he reached the exit. Following the route, she/he saw two landmarks. Whenever she/he saw the landmark, she/he was asked to identify each landmark and try to remember the location of each landmark relative to the environment. It would facilitate the recall process for the route replication task. The participant repeated this learning task on the same pre-defined route three times. After three times repetition, all waypoints and the two landmarks were removed. The participant was asked to follow the exactly same route, relying on her/his navigation experience and memory. Each participant was allowed to spend up to 4 minutes for the route replication task. In this task, all participants were clearly informed that achieving accurate route replication was more important than shorter task-completion time or shorter distance to the exit.

This route replication task was performed on three routes; red, blue and yellow routes in order. However, for the evaluation of route knowledge acquisition, the route replication task on the red route was only considered. Since the single maze was used and some parts of three routes are overlapped, the rest of route replication tasks on blue and yellow routes could be influenced by the prior route experience. As shown in Figure 4.12, three routes were designed to allow the participants to experience with the overall layout of the maze, so that they were able to develop survey knowledge as well as route knowledge.

2. *Free exploration in the last sub-session*

After a participant experienced with three pre-defined routes, the participant was allowed to explore the whole maze within 10 minutes. Six landmarks (no waypoints) were placed

at their original locations as appeared during the first three sub-sessions. All participants were asked to first find all six landmarks to recall the location of each landmark. After the participants found all six landmarks they were allowed to freely navigate. They were also allowed to restart from the entrance, if desired.

After completing the maze navigation tasks (including route replication tasks and free exploration), the participants completed a questionnaire to measure their survey knowledge acquisition.

Also, Witmer-Singer's Presence Questionnaire (PQ) [120] was provided to all participants at the end of the study, so that we were able to examine the subjective sense of presence of the participants in three NavTechs.

Measurements on Spatial Knowledge

1. *Route knowledge acquisition*

The performance of route knowledge acquisition was evaluated by measuring the accuracy of route knowledge acquired. Measuring the accuracy of route knowledge acquired from participants was very challengeable. Our maze was designed with several possible routes from the entrance to the exit, so that we could not simply use the number of wrong turns for assessing route knowledge. Due to the same reason, we could not use the shortest traveled distance to evaluate the accuracy of route knowledge because there was the case that participants skipped some parts of the pre-defined route (i.e., reference path). As shown in Figure 4.13, the traveled paths of participants quite varied. In addition, the traveled distance can include jitter as much as the corridor's width since the maze's corridors have 2 meters width. In addition, all participants were told that they could use up to 4 minutes to finish the route replication task until they achieved the task's goal, i.e., finding the exact same route as they learned. Hence, the traditional measurements, such as shortest traveled distance and task-completion time, were not applicable to our evaluation.

Hence, we developed an evaluation method to assess route knowledge acquired of each par-

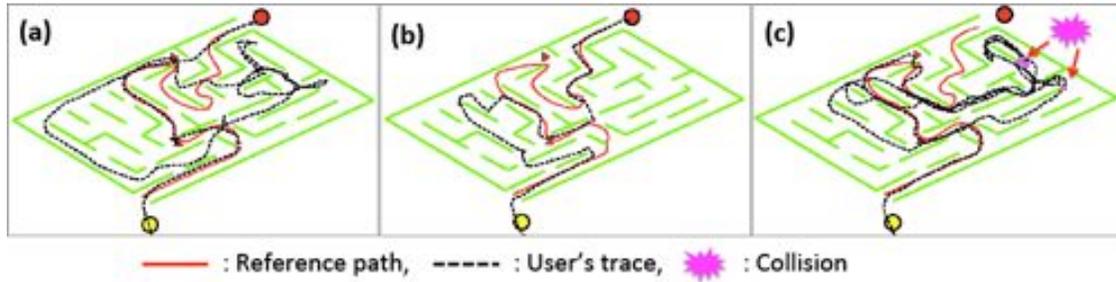


Figure 4.13: Examples of users' traveling data for the route replication task: (a) JS user (b) JS_m user (c) SF-WIP user; red line is a reference path, black dots are a trace of user's traveling, magenta blobs present the collisions with walls.

participant by calculating *penalty scores*. We first defined “decision nodes” and “traveled segments” (straight or curved line between two nodes) over the maze area. Each decision node has a decision probability. We compared a participant's traveled segments with the segments of a reference path to determine how many missing and wrong segments the participant made during the route replication task. Based on the results of the comparison, the penalty scores of each participant were calculated using different weight values depending on the probability of each node. This penalty score determined the accuracy of route knowledge acquired by each participant. For example, if the penalty score was 0, then the participant's route knowledge on the route was perfect. If Participant A had bigger penalty score than Participant B, then we can determine that Participant B acquired more accurate route knowledge than Participant A.

In our maze, there are two types of decision nodes with either $\frac{1}{3}$ probability ($P_a = \frac{1}{3}$) (when there are three possible choices on a node) or $\frac{1}{4}$ probability ($P_b = \frac{1}{4}$) (when there are four possible choices on a node). Thus, the equation to calculate the penalty score of a participant is as follows,

$$S_{penalty} = P_{ms} \times N_{ms} + P_a \times N_{ms,a} + P_b \times N_{ms,b},$$

where P_{ms} is a penalty weight for the missing segments, N_{ms} is the number of missing seg-

ments, $N_{ms,a}$ is the number of wrong segments with P_a and $N_{ms,b}$ is the number of wrong segments with P_b .

The penalty weight for a missing segment can be as desired, such as $\frac{1}{4}$, $\frac{1}{3}$, $\frac{1}{2}$, or 1. Since participants were asked to find the traveled and learned route within 4 minutes and they were told that the accuracy of route replication was the most important, they were expected to do so within the given time. The more number of missing segments on the reference route indicates that the participant did not do what was expected from the participant for the experiment, compared to the participant with the less number of missing segments. Hence, the penalty weight for a missing segment was applied with a greater value than $\frac{1}{3}$, which was the biggest probability used for wrong decision nodes. For our evaluation equation of the accuracy of route knowledge, we attempted to use both $\frac{1}{2}$ and 1 as the penalty weight values for a missing segment.

2. Survey knowledge acquisition

Drawing a map is a common and intuitive method to assess the person's spatial knowledge acquisition, especially survey knowledge, about the environment. Hence, a sketch map has often been considered as a good tool when examining a cognitive (mental) map (i.e., survey knowledge) [7]. However, an issue with the sketch-map-based evaluation is that it can be biased due to individuals' drawing ability. In addition, it can be even more difficult to judge one's sketch map about the environment with less visual information [7] such as the maze used in our study. Therefore, we defined a maze-map based multiple-choice question to assess survey knowledge acquisition of a participant. A multiple-choice with six 2D maps was provided to participants after they completed all tasks in the experiment. Participants were asked to select a correct maze out of six choices, in which they navigated during the experiment tasks.

4.4.2 Results

Route Knowledge Acquisition

It was confirmed that the collected data (i.e., *penalty scores* of participants) per group follows normal distribution by the Shapiro-Wilk test. Figure 4.14 shows the means of the penalty scores from the (red) route replication task when the penalty weigh value for a missing segment (P_{ms}) is 1; JS_m: $M=7.71$, $SD=4.86$; JS: $M=7.96$, $SD=5.15$; SF-WIP: $M=4.96$, $SD=4.1$.

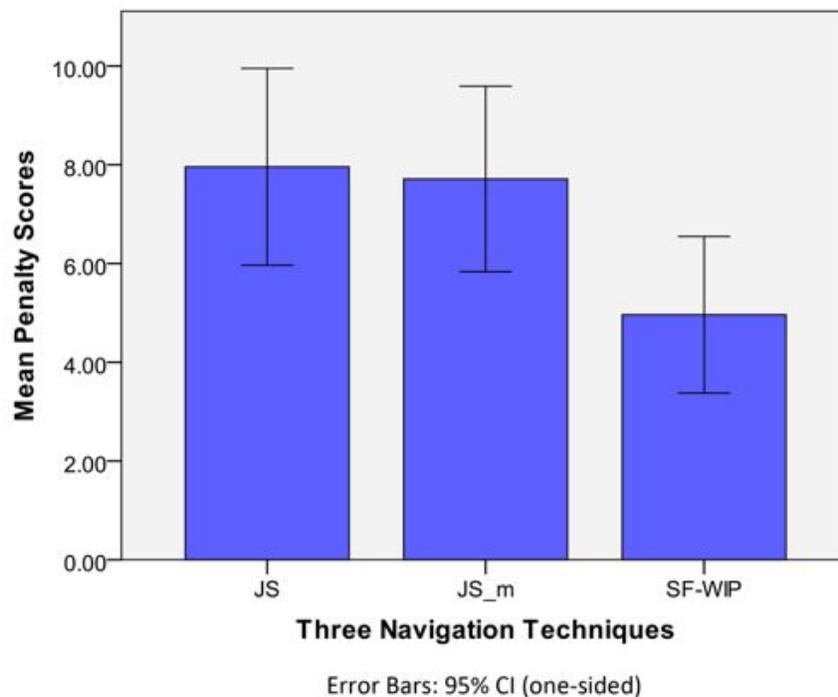


Figure 4.14: Mean penalty scores from the (red) route replication task, when the penalty weight for missing segments is 1.

In order to test our hypothesis, *the JS_m would be more effective than the JS on spatial knowledge acquisition while the SF-WIP would be more effective than the JS_m on spatial knowledge acquisition or the SF-WIP and the JS_m would have equal effect on spatial knowledge acquisition*, we conducted independent-samples t-tests (one-tailed) at 95% confidence level to compare the means on the penalty scores of the JS_m vs. the JS and the JS_m vs. the SF-WIP. There was no significant

difference on the effect of route knowledge acquisition between the JS_m and the JS when P_{ms} is either 1/2 or 1. However, there was a significant difference on the effect of route knowledge acquisition between the JS_m and the SF-WIP when P_{ms} is 1/2; t(38) = 1.93, p < .05 (= .03) when P_{ms} is 1; t(38) = 1.86, p < .05 (= .035). The results were also similar to the results of comparison between the SF-WIP and the JS; t(38) = 2.03, p < .05 (= .024) when P_{ms} is 1; t(38) = 1.86, p < .05 (= .035) when P_{ms} is 1/2. The results are summarized in Table 4.3. Thus, our study result showed that the JS_m was not effective as much as the SF-WIP on route knowledge acquisition.

Table 4.3: Results of t-test to compare the penalty scores in JS vs. JS_m, and JS vs. SF-WIP. Two penalty-weight values (i.e., 0.5 and 1) are attempted for missed segments.

Weight Value (P _{ms})	JS _m vs. JS	JS _m vs. SF-WIP	SF-WIP vs. JS
0.5	p > 0.05(= 0.486)	p < 0.05(= 0.035)	p < 0.05(= 0.035)
1	p > 0.05(= 0.439)	p < 0.05(= 0.03)	p < 0.05(= 0.024)

Survey Knowledge Acquisition

Based on the collected data from the maze-map based multiple-choice question, Table 4.4 shows how many participants of three groups selected the correct answer.

Table 4.4: Result of the multiple-choice question for survey knowledge acquisition.

Interface groups	#of users for correct selection
JS	6
JS _m	9
SF-WIP	9

In order to evaluate the performance of participants on survey knowledge acquisition with this result, we hypothesize that:

Without survey knowledge, the probability to randomly choose the correct answer is $\frac{1}{6}$, while the probability for the wrong answer is $\frac{5}{6}$, when the maze-map based multiple-choice question has six items. If the probability of the correct answers in any NavTech group is found statistically outperforming over $\frac{1}{6}$, we can conclude whether the NavTech group’s users acquired survey knowledge after the maze experience.

Due to our specific test-metric for survey knowledge acquisition, we were not able to conduct any mean-comparison statistical test to evaluate the performance of participants on survey knowledge acquisition. Rather, we focused on which group’s participants acquired survey knowledge of the maze environment.

A one-sample chi-square goodness-of-fit-test was conducted to see if the number of participants who chose the correct answer in each NavTech group significantly differ from the expected number of participants who randomly chose the correct answer. Since our sample size per group is 20, 3.3 ($\frac{1}{6}$ probability) is the expected number for the correct answers per group. The current sample size (i.e., 3.3) per choice is smaller than the typically-suggested minimum size (usually ‘5’) to conduct a one-sample chi-square. Hence, we analyzed our data with a generalized Fisher’s exact test method that can be used for small sample size. Its results were presented on the rightmost column in Table 4.5.

Table 4.5: Results of χ^2 goodness-of-fit-test indicate that participants with JS_m and SF-WIP but not with JS techniques acquired survey knowledge.

Interface	Chi-Square(χ^2)	p-value	p-value (with the generalized Fisher’s exact test)
JS	2.543	> .05(= 0.111)	> .05(= 0.128)
JS _m	211.514	< .05(= 0.001)	< .05(= 0.003)
SF-WIP	11.514	< .05(= 0.001)	< .05(= 0.003)

Table 4.5 shows the result of the statistical test. At the $\alpha = 0.05$ level of significance, there is

enough evidence to conclude that the participants with the JS_m and the SF-WIP NavTechs acquired survey knowledge, whereas there is no enough evidence for the participants with the JS NavTech. Thus, our study result showed that the JS_m was effective as much as the SF-WIP on survey knowledge acquisition while the JS did not effectively support the participants to acquire survey knowledge.

Spatial Correlation

We wondered if there is any correlation between three NavTechs and the spatial ability test designed by Psychology researchers. We conducted Pearson's Correlation test to examine whether or not the participants' innate spatial ability has any correlation with their spatial knowledge acquisition in the virtual space. The results of self-report of SOD [33] and PTSOT [34] tests were used to examine this correlation. Interestingly, the result only of the SF-WIP NavTech on route knowledge acquisition was correlated in both spatial ability tests: $R=-0.459$, $p < 0.05$ ($= 0.042$) in self-report SOD and $R=0.455$, $p < 0.05$ ($=0.044$) in PTSOT. We discuss this result in §4.4.3.

Subjective Sense of Presence

In order to examine the subjective sense of presence, Presence Questionnaire (PQ) [120] was used, which has three categories; *Involvement*, *Adaptation/Immersion*, and *Interface Quality*. Because three categories of PQ have different numbers of items, i.e., 56, 49 and 21 items, respectively, we normalized the raw scores of PQ. Figure 4.15 shows the means of the normalized scores of PQ in three NavTechs based on three categories. We compared the normalized scores of PQ using one-way ANOVA (at the $\alpha = 0.05$ level of significance) that had one between-participants factor of three NavTech groups. The results showed that there were significant differences on the participants' sense of presence in all three categories; *Involvement*: $F(2, 57) = 9.451$, $p = .000$; *Adaptation/Immersion*: $F(2, 57) = 6.295$, $p = .003$; *Interface Quality*: $F(2, 57) = 4.425$, $p = .016$.

Fisher's LSD post-hocs showed that significantly higher sense of presence was found in the JS_m

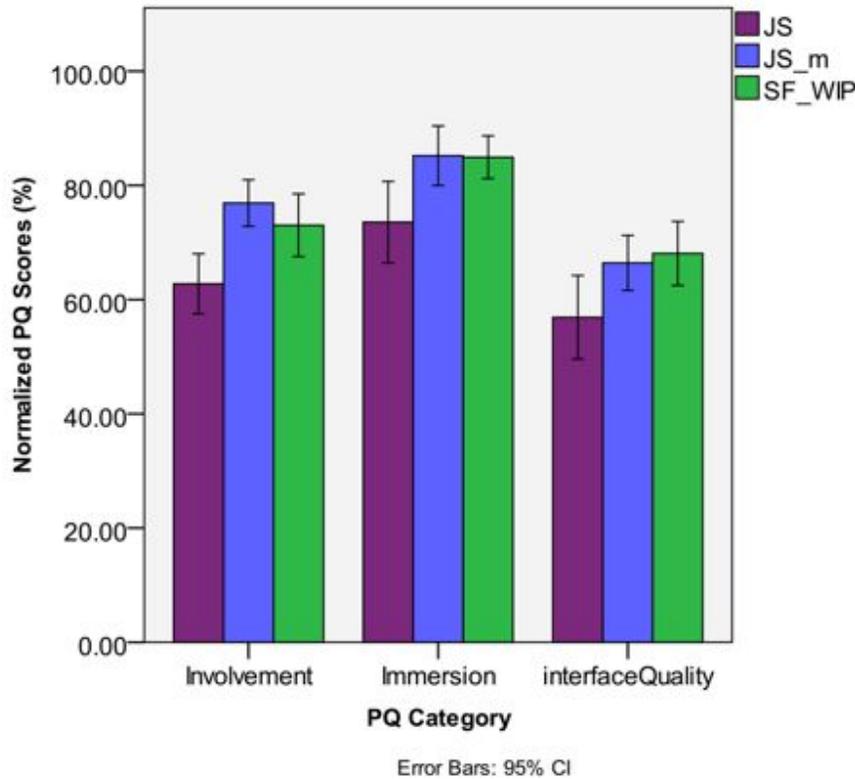


Figure 4.15: Normalized scores of Presence Questionnaire (PQ). Error bars: 95% CI. In all three categories, two body-based NavTechs, i.e., JS_m and SF-WIP NavTechs, showed the similar level of presence that is higher than that of the JS NavTech.

and the SF-WIP groups than in the JS group to all three categories; *Involvement*: $p = .000$ (JS_m vs. JS) and $p = .003$ (SF-WIP vs. JS); *Adaptation/Immersion*: $p = .003$ (JS_m vs. JS) and $p = .004$ (SF-WIP vs. JS); *Interface Quality*: $p = .022$ (JS_m vs. JS) and $p = .008$ (SF-WIP vs. JS). There were no significant differences found in the other pairwise comparisons.

4.4.3 Discussion

In our between-subjects design, the study results showed that our body-turn based NavTech (JS_m) outperformed the JS on survey knowledge acquisition while there was no significantly different effect between the JS_m and the JS on route knowledge acquisition; $JS_m \approx JS$ on route knowledge

acquisition but $JS_m > JS$ on survey knowledge acquisition. On the other hand, it was shown that the SF-WIP NavTech outperformed the JS and the JS_m NavTechs on route knowledge acquisition and outperformed the JS NavTech on survey knowledge acquisition; $JS_m \simeq$ SF-WIP on survey knowledge acquisition while SF-WIP $>$ JS on both route and survey knowledge acquisition.

These results can support our theoretical reasoning because the body-turn action (i.e., partial action of the original ‘walking’ action) was effective for survey knowledge acquisition, meaning that the body-turn action played an important role for spatial learning.

Our study also showed that our body-turn based design approach with the JS_m can resolve the issues of walking-like NavTechs, and provide the possible answer to our key research question as the JS_m showed the effectiveness for survey knowledge acquisition more conveniently, compared to the SF-WIP (i.e., a walking-like NavTech). Since we simply employed the wand device which is commonly used for immersive VEs as if a mouse is commonly used for desktop computers, there was no additional complex system configuration. Since JS_m allowed the participants to turn in place, no extensive space was necessarily used. Although we did not systematically measure the differences of the JS_m and the SF-WIP on whole-body fatigue, there must be additional muscle groups (i.e., lower limbs) that were continuously used for the SF-WIP and consequently whole-body fatigue should be much less with the JS_m . It would be interesting further work to quantify whole-body fatigue of two NavTechs and compare the quantified measurements. However, since the JS_m was only effective for survey knowledge, the JS_m would be not sufficient to support effective spatial knowledge as much as walking-like NavTechs.

In the remaining parts, we discuss our observations and experiences from our study in this chapter.

Possible Answer to The Different Results of Previous Studies

Interestingly enough, our study results may be able to explain the conflict results that previous studies showed [77, 83]. As we discussed in §2.3, two studies of Riecke *et al.* [77] and Ruddle *et al.* [83] showed the different results. Ruddle *et al.* [83, 86] argued that body-control based

translation (i.e., bipedal walking) is necessary for establishing effective cognitive map in direction and distance estimates. On the other hand, Riecke *et al.* [77] argued that body-control based rotation would be enough for effective virtual navigation in reducing searching time. Riecke *et al.* tried to find the reason of the different results from the different experimental factors, such as desktop-display [83] versus head mounted display (HMD) [77]. Based on our study results, we can provide another plausible reason to explain the different results. The different results might be from the integrated assessment for two different types of spatial knowledge. If we consider that body-turn is partial action of the ‘walking’ action, body-turn even without gait movement should be effective for spatial knowledge acquisition as our theoretical reasoning suggests. As demonstrated in our study, the participants in the JS_m group showed that they acquired survey knowledge as well as the participants in the SF-WIP group, but unlike the participants in the JS group. Hence, body-turn action would be more effective for survey knowledge acquisition but not for route knowledge acquisition. We conjecture that the survey knowledge acquired by body-turn might be more dominantly affecting for assessing cognitive map in the study of Riecke *et al.* [77], while the route knowledge acquired by gait movement (combined with body-turn) might be more dominantly working for assessing cognitive map in the study of Ruddle *et al.* [83, 86].

Non-Traditional Metrics for Route and Survey Knowledge Acquisition

Since there is little research to investigate the effect on route and survey knowledge acquisition separately, the challenge in our study was identifying the experiment tasks and assessment metrics. As [85] argued, assessing route and survey knowledge with different metrics is needed for the different types of spatial knowledge.

As we described in the beginning of this chapter, VEs can be designed as small-scale or large scale with rich visual information, or visually impoverished small-scale or large-scale space, depending on the purposes of different applications. In addition, the focus of our study was more on improving spatial learning effect rather than improving the interface’s efficiency. Hence, we needed to identify the experiment tasks and metrics appropriately to our study purpose while consider-

ing the environmental characteristics, so that we were able to assess route and survey knowledge acquisition separately in a large-scale, large-extent and visually impoverished maze space.

In order to measure route knowledge, there can be several possible tasks, such as route replication task, route distance estimation task, verbal descriptions of routes, route recognition tasks, and landmark sequencing tasks. More generally, route replication task is used to measure route knowledge by using the number of wrong turns taken by participants, so that the accuracy of route knowledge can be simply calculated [6]. However, as illustrated in Figure 4.11, the accuracy of route knowledge cannot be simply calculated by the number of wrong turns, especially when the maze has several routes from the entrance to the exit. Hence, we took the route replication task to assess route knowledge, but needed to provide a new evaluation method. Consequently we developed an evaluation method of route knowledge acquisition by calculating *penalty scores*.

Although measuring the distance traveled between places for route knowledge and the direction estimate for survey knowledge is commonly used, it is noticeable that these metrics were originally suggested for measuring cognitive maps in a visually rich environment (or ecological environment) [102], but not in a visually impoverished environment, such as our maze with big walls with a green solid-color and corridors. As aforementioned, a sketch-map is a good tool to examine a person's survey knowledge acquisition [7]. Due to the issues with a sketch-map, such as biased subjective judgment or individuals' different drawing ability, other variations have been proposed [122], for example, by using the map-reconstruction task to measure survey knowledge acquisition. However, this map-reconstruction task is mostly based on landmarks, including terrain or environmental features. The map-reconstruction task is hardly applied to visually impoverished environments (e.g., maze environment). Hence, we assessed survey knowledge by using the map-based multiple choice question, which is an objective metric, and demonstrated how it can be used to assess survey knowledge by using the chi-square goodness-of-fit-test.

As a part of evaluation of survey knowledge acquisition, we attempted to examine the participants' direction estimates. After all experiment tasks were finished, we provided all participants with a pen and paper to draw an arrow indicating the direction from the entrance to each landmark on

a blank half-circle given only with the entrance point. The participants had to only rely on their acquired spatial knowledge to perform this test. We used this pen and paper for drawing the arrow rather than allowing the participants to point out the estimated direction [86] or take the shortcut to the target [45, 69] in the virtual space because continuously perceived visual information by looking at the virtual space during our measurement process might influence the survey knowledge already acquired and affect our assessment as a confound.

For the direction estimates of each participant, we measured the angular deviation from the correct direction of each landmark. However, the results for the six landmarks in three NavTech groups were not consistent, but just varied, and consequently there were no significant differences in any pairwise comparisons. We realized that this drawing test might produce unreliable-direction-estimation in our large-scale and complicated maze environment because the participants' believed target position and direction are inevitably distorted by human errors in distance and direction estimates [36]. The errors can be larger in the large-scale space than in the small-scale space. In addition, the high complexity of the routes induced by many turns at non-right angles can cause more errors in direction estimate as indicated in [102]. Thus, the large variance of measured direction estimates with six landmarks can be explained by the large-scale environment and the high complexity of the routes in our maze. We excluded this measurement of direction estimate from our data analysis since the large variance cannot be resolved by the small sample sizes (i.e., 20 participants (small samples) per group in our study). Any further data analysis on this measurement was not continued.

Effect on Sense of Presence

The results of the subjective sense of presence using PQ (§4.4.2) were quite interesting. First of all, the comparisons of the SF-WIP and the JS groups in three categories (*Involvement*, *Adaptation/Immersion* and *Interface Quality*) of PQ showed the consistent results as [90] and [104], i.e., walking-like NavTechs enhanced the sense of presence significantly higher than the wand-joystick common NavTech.

Moreover, the participants of the JS_m group also showed that they had higher sense of presence in all three categories, compared to the participants of the JS group. The results can be explained in a few ways. Since the JS_m is based on partial action of the original ‘walking’ action, the sense of presence would be still remained. On the other hand, the dominant factor to influence the subjective sense of presence might be ‘body-turn’ rather than “cyclic leg-movement”. Based on our reasoning, the former explain was more plausible, but further investigation would be needed to correctly explain the result.

Experience with SF-WIP

Apart from our main purpose of this study, the SF-WIP showed that it worked well for virtual navigation as a walking-like NavTech in our comparative study. The SF-WIP allowed the dynamic speed of virtual movement, corresponding to participants’ walking speed. In addition, the SF-WIP was easily implemented using smartphones and provided a complete wire-free solution and dynamic movement speed from slow walking to fast running. It allowed us to observe various behaviors of participants during navigation in the maze. For example, we observed that participants mostly ran when they moved along aisles of the maze without turns. When the participants had to turn a lot, they walked slowly. Some participants tried to use some hand gestures to help remember the route. Thus, the SF-WIP provided some opportunities for participants to navigate the maze more comfortably (or naturally), in terms of dynamic speed control as well as wire-free and hands-free.

An interesting result was the correlation with two spatial ability tests, self-report SOD [33] and PTSOT [34], showing that there was the correlation only with the SF-WIP, but not with the JS or the JS_m NavTechs. The correlation between the SF-WIP and the spatial ability tests was only found in the result of route knowledge acquisition. Given the fact that two spatial ability tests were verified in some psychological studies [33, 34], we assume that the SF-WIP supported the natural navigational experience similar to that of walking in the real world.

One noticeable weakness of the SF-WIP (but the common weakness with the other WIP NavTechs)

is that it does not support moving backward or moving sideways without turning. Participants can only move forward in the direction that the upper body is pointing. It might cause some additional disorientation in navigational tasks, especially when participants should make a turn at larger a right angle. Actually, 3 out of 20 participants complained about these unsupported functions of the SF-WIP. Related to this weakness, there was unintended movement. Due to the characteristic of WIP, whenever the participants moved their legs, the SF-WIP detected the leg-movements as walking forward and virtual movement was made accordingly. It sometimes happened when turning in place if participants provided a large amount of leg-movement. Although the participants understood how to handle it when they turned in place, this issue should be considered in future work.

4.5 Chapter Summary

In this chapter, we evaluated body-turn based design approach using JS_m . We presented how to develop the body-turn based NavTech (JS_m) and described our evaluation of the JS_m through a comparative study in a large-scale, large-extent and visually impoverished virtual space (i.e., maze) using a CAVE virtual environment system. Two different types of NavTechs, a common non-body-based NavTech (JS) and a walking-like NavTech, were compared with JS_m . In particular, we newly developed sensor-fusion walking-in-place (SF-WIP) to provide the walking-like NavTech not only because the existing WIP NavTechs were hardly adopted to our CAVE system but also because some potential issues, e.g., latencies, tethered interface and no support of dynamic walking-speed change, were not fully addressed yet. After our validity test of the SF-WIP, we employed the SF-WIP for our comparative study. Our comparative study focused on two comparisons, JS_m vs. JS and JS_m vs. SF-WIP.

In the comparative study, our evaluation was focused on measuring the accuracy of route and survey knowledge acquired through the route replication task and extensive exploration of the maze. We provided our own evaluation methods because the known evaluation methods such

as shortest traveled distance, shortest task-completion-time or counting wrong turns, were not applicable to our comparative study. Route knowledge acquired by a participant was assessed using *penalty scores* given to the wrong and missing segment(s) that were not in the reference route while survey knowledge acquisition of a participant was examined using a map-based multiple-choice.

Our analysis on route knowledge acquisition showed that the SF-WIP supported the participants to acquire more accurate route knowledge than the other NavTech groups, i.e., JS and JS_m. Regarding survey knowledge acquisition, our study results statistically showed that the participants of JS_m and SF-WIP groups acquired survey knowledge while the participants of the JS group did not acquire survey knowledge.

Thus, our comparative study described in this chapter supports that one of our action-inspired approaches, i.e., body-turn based approach, can be used to design effective NavTechs for survey knowledge acquisition, by demonstrating that the body-turn based NavTech (JS_m) can effectively support survey knowledge acquisition. Observing our study results described in this chapter and previously performed study results [77], it appears that body-turn may be a dominant factor to influence the effect on survey knowledge acquisition in visually-impooverished virtual space.

Our study also suggests that walking-like and body-turn-based NavTechs could be selectively used. This suggestion can be guidance on the choice of action for some applications to minimize the effort to design/develop effective NavTechs for spatial knowledge acquisition. Implementing walking-like NavTechs would need more time, more complex hardware, more complex algorithms and lots of usability studies for fine-tuning, compared to body-turn or non-walking common NavTechs. If learning spatial layout of the environment (i.e., survey knowledge) is more important to some applications, a body-turn based NavTech would be enough. However, if there are the cases that the full effects of route and survey knowledge are needed, walking-like NavTechs would be more likely suggested as many relevant studies suggest. Further investigation would be beneficial to support our guidance to provide more detailed guidelines.

In addition, since our test VE is based on a large-scale, large-extent and visually impoverished space, the results of our study support that people can be trained in such environments to effectively

acquire spatial knowledge for some applications, such as military training in large abandoned buildings or deserted areas, firefighter training in burn buildings with no signs, covered by fire and smoke, and large-scale disaster rescue training in earthquake or mine.

Chapter 5

Design and Evaluation of Action-Transferred Approach

We proposed an action-transferred approach as one of action-inspired approaches to design effective navigation techniques (NavTechs) for spatial knowledge acquisition in §3.2.2. In this chapter, we present how a new NavTech is designed and implemented as an example of our action-transferred design approach. Then we demonstrate the effectiveness of the new NavTech in spatial knowledge acquisition, referring to the effectiveness of our action-transferred design approach.

As mentioned in §3.2.2, our action-transferred NavTech is drawn on our common intuition of “finger-walking”. Hence, we present the design and implementation of the “finger-walking” based NavTech, named “finger-walking-in-place (FWIP)”, and describe our evaluation of the FWIP through a formal comparative user study in a CAVE virtual environment system.

5.1 Finger-Walking-in-Place: *FWIP*

Since the FWIP is a newly designed NavTech and has never been prototyped, we needed to go through several iterations for designing and implementing the FWIP through several usability stud-

ies.

5.1.1 Design

We first determined how to control navigational components (i.e., orientation and translation) by two fingers. In the real world, when you walk or run, the ground gives an equal and opposite push to you, called “ground reaction force (GRF)”, so that you can move forward (or backward). We used the same principle of GRF to design our NavTech. However, in order to avoid the physical movement of the whole-body, our design is based on *action in place* similar to *walking in place*, which itself is different from the natural walking. We could have four variations of the NavTech for “walking forward”, “walking backward”, “walking sideways” and “turning in place”. However, we chose three variations only for “walking forward”, “walking backward” and “turning in place” because “walking sideways” can be easily integrated into “walking forward”. Since the horizontal 2D plane of 3D virtual space can be mapped to the surface for “finger-walking”, “walking forward” and “walking backward” with any angles allow a user to move to any direction including *sideways*. Figure 5.1 shows that how the translational control of navigation is designed for “finger-walking forward” (Figure 5.1a and Figure 5.1b) in any direction (Figure 5.1c).

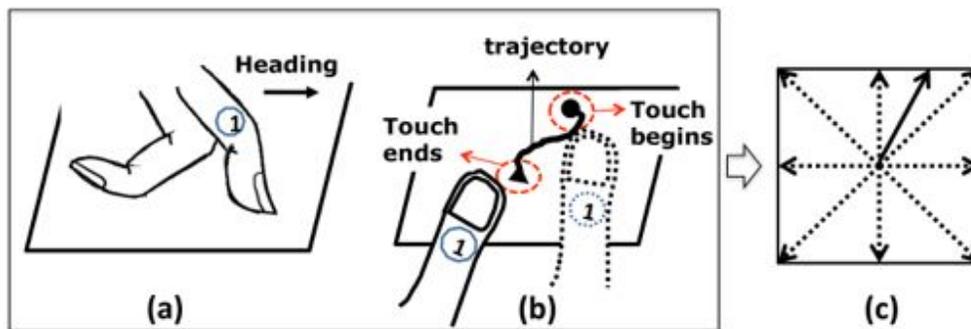


Figure 5.1: Translational control of the FWIP: side view (a) and top view (b) of “finger-walking” on the horizontal plane. Copyright ©2010 Springer. (c) Top view of the horizontal plane showing that virtual translation is possible to any direction on the horizontal plane in 3D, as indicated by the arrows; notice that the direction of finger-movement is opposite to the direction of virtual movement.

Two variations, “walking forward” (Figure 5.2a) and “walking backward” (Figure 5.2b) can be simply mapped to two fingers by mimicking the motion pattern (i.e., cyclic swing and stand phase) of bipedal walking. However, for “turning in place” of walking, it is very difficult for two fingers to directly mimic the turning motion of two legs and the whole body because the wrist can be hardly turned more than 90 degrees. Instead of directly mapping the turning motion of two legs to two fingers, we adopted a concept of *pivot and push*, which is based on the GRF principle. While one finger is having a pivot point, the other finger can form an arc around the pivot by applying a pushing force in the opposite direction of rotating one’s virtual viewpoint. The angle of the arc determines the rotation angle of one’s viewpoint in the virtual space (Figure 5.2c).

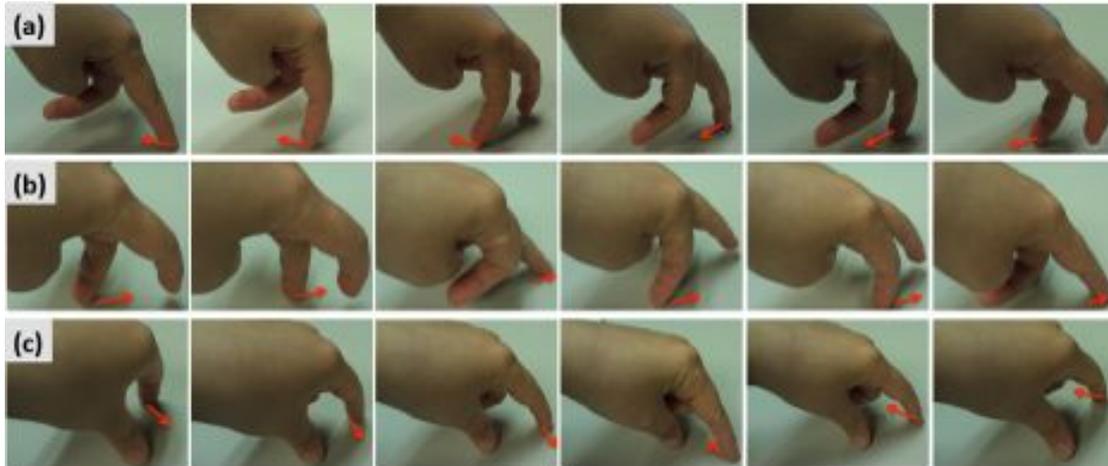


Figure 5.2: Design of the FWIP: (a) walking forward (and sideways), (b) walking backward, and (c) turning. The small arrows show the direction in which the finger pushes. The heading direction (i.e., virtual movement) is opposite to the direction of push.

For the design of the rotational control with “finger-walking” for navigation, we initially adopted the dragging distance to determine the rotation angle of the virtual viewport (Figure 5.3a). Then we changed to using the angle of the arc to determine the rotation angle of one’s viewpoint in the virtual space (Figure 5.3b) because non-pivot finger actually forms an arc, not a straight line. We found this refined design through the iterative process of design and implementation [43, 44, 45]. While our previous preliminary comparative study [45] was performed using the rotational control shown in Figure 5.3a, our comparative study described in this dissertation was performed using the

rotational control shown in Figure 5.3b. We did not perform the usability study for the type shown in Figure 5.3b because the logged data of two types of rotational control showed that this changed design did not affect the resultant virtual orientation. Thus, we named our NavTech, “Finger-Walking-in-Place” (FWIP) as FWIP is not designed for physically moving around but acting in place.

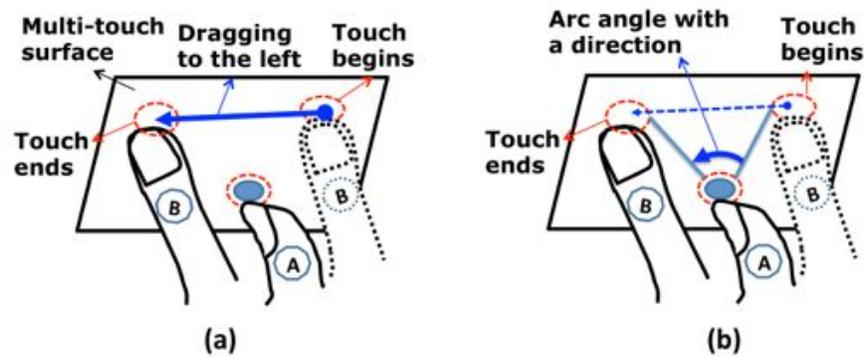


Figure 5.3: Rotational control of the FWIP: (a) the dragging distance determines the rotation angle of a virtual viewpoint. (b) the arc angle determines the rotation angle of the virtual viewpoint.

5.1.2 Implementation

Our design of FWIP can be implemented on any device, including multi-touch devices or worn-gloves, as long as those devices can detect finger-movement. We chose multi-touch devices which are popular consumer products on the market that come with software development libraries.

While our action-inspired design approach was in progress, the initial prototype of FWIP has been introduced [43] and implemented on several multi-touch devices, such as Lemur [43] or iPhone [44] as shown in Figure 5.4. Details are described in [43, 45]. From the previous preliminary studies, we observed that the phone-sized (i.e., small-sized) touch-surface might cause some constraint to perform the FWIP, especially for rotational control. Hence, we refined the FWIP using the final design of the rotational control (Figure 5.3b), and implemented it on iPad (approximate width: 14.8 *cm* and height: 19.7 *cm*) for evaluating our action-transferred design approach described in this dissertation.

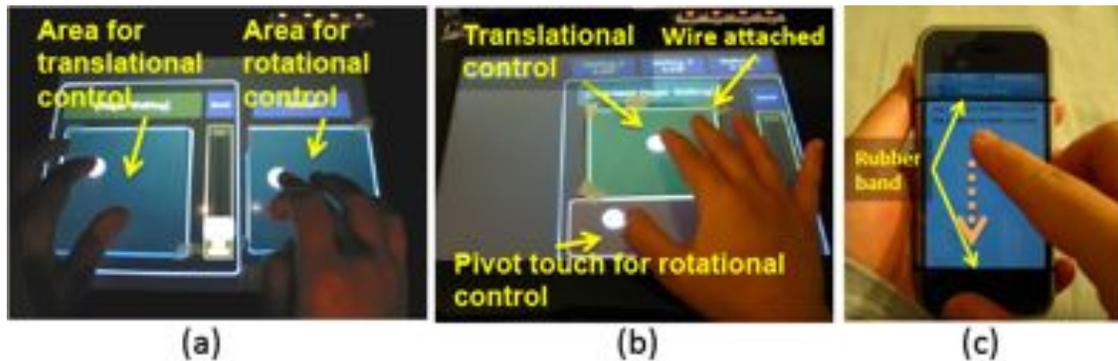


Figure 5.4: (a) two-handed FWIP; initial design on Lemur device [43] (b) one-handed FWIP on Lemur device [45]. Copyright ©2010 Springer. (c) one-handed FWIP on iPhone [44].

Design and implementation of the FWIP can satisfy the part of our research question, i.e., convenient use, compared to walking-like NavTechs. Transferring the ‘walking’ action to the fingers can resolve the two issues, i.e., “the whole-body fatigue” and “requirement of large-controlled space” because the whole-body movement is not necessary for the FWIP. By adopting the consumer product on the market to implement the FWIP allowing users to operate the FWIP with the bare fingers, we also resolved the third issue, i.e., requirement of complex system configuration for walking-like NavTechs.

5.1.3 Lessons Learned from The Preliminary Comparative Study

For the initial evaluation of the FWIP, we conducted a preliminary comparative user study [45] to investigate whether or not the FWIP NavTech would support users to acquire spatial knowledge better than a common NavTech, i.e., JS (§4.2.1), in the CAVE system. The preliminary study was designed with a similar experiment tasks and procedure described in Peterson *et al.* [69]. To the best knowledge of the author, Peterson *et al.* [69] was the only study to examine route and survey knowledge acquisition separately using some complex tasks in a single virtual space.

Our preliminary study [45] showed that the better route knowledge acquisition was supported by the FWIP than the JS. This preliminary study results were very promising, meaning that our action-

transferred design approach can be effective for spatial learning although there was no significant effect found on survey knowledge acquisition in [45].

We thoroughly reviewed our preliminary experiments and found that there were some limitations in the experiment design and in the evaluation method for survey knowledge acquisition. In order to evaluate the survey knowledge acquisition, we asked the participants to learn only one route for the given virtual maze and to perform a task by taking a shortest path from the entrance to the exit by moving through all objects and walls. Since “survey knowledge” refers to a ‘global’ spatial representation of the environment, the experience with one pre-defined route should hardly provide the participants with the opportunity to acquire survey knowledge.

In addition, the evaluation method used for survey knowledge acquisition might be confounded. The accuracy of “direction estimation” could be measured by the task, “taking a shortest path” as we did in [45]. However, measuring direction estimation cannot replace measuring the accuracy of survey knowledge. Note that our interest was in assessing spatial knowledge, but not assessing direction estimate although direction estimate can be a partial measurement to assess spatial knowledge (details are in §4.4.3). By the definition of survey knowledge, if people acquired survey knowledge, they would be able to have a mental representation like a map without seeing the actual environmental information. Hence, the task, “taking a shortest path” could be confounded by the previously built spatial memory/knowledge because the participants were allowed to look around until they completed the task of finding the shortest path. Hence, our comparative study to evaluate our action-transferred approach should be designed by reflecting the lessons learned from our preliminary study, in particular for assessing survey knowledge.

Since our experiment for evaluating the body-turn based approach (Chapter 4) was designed after we revised this preliminary study, we adopted the same experiment design as used in Chapter 4 to examine the effect of our action-transferred approach on route and survey knowledge acquisition separately in a large-scale, large-extent and visually impoverished space. With the experiment design, the participants were able to experience with the whole environment and consequently our evaluation was able to focus on the accuracy of survey knowledge acquired as well as route knowl-

edge acquisition. In addition, we adopted the SF-WIP (§4.3) as well as the JS (§4.2) described in Chapter 4, in order to investigate the effect of the FWIP on spatial knowledge acquisition, compared with a walking-like NavTech as well as compared with a common NavTech,

5.2 Evaluation: Action-Transferred NavTech

For this evaluation, we hypothesized the effect of FWIP (i.e., action-transferred NavTech) on spatial knowledge acquisition to be twofold:

Hypothesis 1: If the concept of action-transfer works for spatial learning, the FWIP supports more effective spatial knowledge acquisition, compared to a wand-and-joystick common NavTech, as other empirical studies with walking-like NavTechs demonstrated their effectiveness for spatial knowledge acquisition.

Hypothesis 2: There is no difference on spatial learning between FWIP and walking-in-place (WIP) NavTechs if the transferred action (i.e., FWIP) and the original action (i.e., WIP) have the shared representation (i.e., same abstract form) stored in our brain and spatial learning is dependent on the action, not biological effectors.

We performed a comparative user study using a between-participants design with three NavTech groups to test our hypotheses. Our interest in this evaluation was to investigate the effect of FWIP technique on spatial knowledge acquisition, especially route and survey knowledge acquisition separately [89], compared to a common NavTech (i.e., wand and joystick based NavTech: JS) and a walking-like NavTech (SF-WIP in this dissertation) in VEs.

In addition we decided to examine the subjective sense of presence of participants. According to [104], walking-like NavTechs (e.g., real walking or walking-in-place) significantly enhanced the subjective rating of presence compared to a wand-and-joystick common NavTech. We wondered whether the subjective sense of presence is also enhanced by the transferred action based NavTech

(FWIP) as much as the original action based NavTech (SF-WIP).

5.2.1 Method

Since the purpose of this comparative study was to investigate the effect of one of action-based approaches, i.e., action-transferred approach, on spatial knowledge acquisition, we followed the exactly same experiment method described in §4.4, regarding “Virtual Environment System” (§4.4.1), “Design of Virtual Space” (§4.4.1), “Pre-experiment spatial ability test” (§4.4.1), “Procedure” (§4.4.1) and “Measurements” (§4.4.1). The only difference is on using different comparisons, i.e., FWIP vs. JS and FWIP vs. SF-WIP, and consequently additional participants were involved.

Three NavTechs

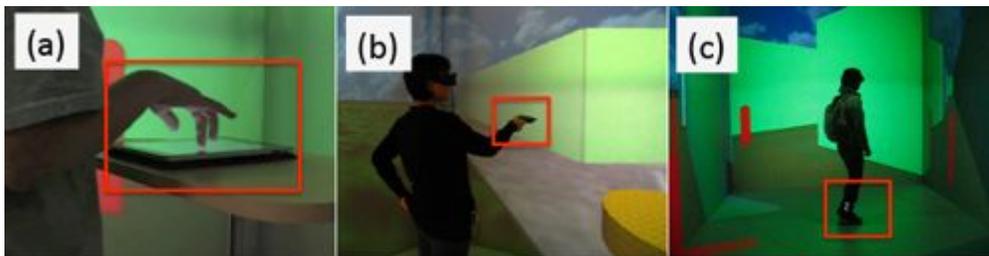


Figure 5.5: Snap shots of users using three NavTechs; (a) FWIP (b) JS (c) SF-WIP.

As aforementioned, we are aiming at comparing the effect of the FWIP and the other two NavTechs on spatial knowledge acquisition. For this study, we refined the FWIP and implemented it on an iPad device after several iterations of design and implementation. The iPad was placed on a table so that the participants using the FWIP were not allowed to move or turn the device or the table (Figure 5.5a). Any physical movement (except for finger-movement and head-movement) was not allowed.

As a common NavTech, we adopted the same JS NavTech described in §4.2.1 (Figure 5.5b). This JS provides dual control for orientation because the joystick is used for both translation and rotation

of the user's viewpoint in a 2D plane while the orientation of the wand is also used to determine the orientation of the user's virtual viewpoint. In addition, there can be a confound here because body-turn (to change the orientation of the wand) as well as the joystick can be used to control rotation. In order to resolve the confound factor, we attempted to use the modified JS NavTech removing the wand's orientation control (i.e., not allowing body-turn), so that users were only allowed to control the joystick for navigation. However, 6 out of 11 users complained about cyber-sickness, such as nausea or dizziness, and had to withdraw from our pilot study (see §5.2.3 for details). Considering the high dropout rates (over 50%), we did not include the modified JS NavTech for our comparative user study.

We employed the sensor-Fusion Walking in Place (SF-WIP) NavTech described in §4.3 (Figure 5.5c) as a WIP NavTech close to natural walking. The SF-WIP was easily implemented by using two commodity smartphones. It was used as a reference NavTech for estimating spatial knowledge acquisition to show how close the effect of the FWIP on spatial learning is to that of a walking-like NavTech.

Participants

We recruited participants with no disability from on-campus listserv and a participant recruiting system maintained by our school. All participants gave a written informed consent for the study. Twenty participants per group were expected. Ten participants withdrew because of severe cyber-sickness, two (2 female) from FWIP group, seven (5 female) from JS group and one (female) from SF-WIP group. Also, the data of two (1 female) participants in FWIP group were excluded due to system malfunctions. Hence, we recruited additional participants so that we were able to collect the data of twenty participants per group, who completed the experiment tasks.

All participants took the spatial ability test described in §4.4.1 before performing the experiment tasks. The sixty participants were randomly assigned to three groups, being gender (10 male and 10 female per group) and spatial ability balanced. An analysis of variance (ANOVA) for SOD and PTSOT results did not show any significant difference between three groups; SOD: $F(2, 59) =$

0.23, $p = .79$; PTSOT: $F(2, 59) = 1.21$, $p = .31$.

Each participant took approximately 90 minutes to complete the experiment, including taking short breaks and responding to the pre-/post-experiment questionnaire. Undergraduate students (nineteen participants per group) were compensated with two course credits. Graduate students (one participant per group) were not compensated but voluntarily participated. Other demographic data for the participants are summarized in Table 6.1.

Table 5.1: Summary of demographic data for the participants

NavTech Group	Age	# of users with VE experiences	# of users who played video games
FWIP	$M = 20.15$, $SD = 1.496$	Female:1, Male:1	Female:3, Male:9
JS	$M = 20.05$, $SD = 1.395$	Female:1, Male:3	Female:7, Male:10
SF-WIP	$M = 20.15$, $SD = 1.663$	Female:0, Male:2	Female:4, Male:9

5.2.2 Results

All participants went through the same experiment procedure as described in §4.4.1. We used the same measurement methods as presented in §4.4.1.

Route Knowledge Acquisition

It was confirmed that the collected data (i.e., *penalty scores* of participants) per group follows normal distribution by the Shapiro-Wilk test. Figure 5.6 shows the means of the penalty scores from the (red) route replication task when the penalty weigh value for a missing segment (P_{ms}) is 1; FWIP: $M=5.41$, $SD=3.89$; JS: $M=7.96$, $SD=5.15$; SF-WIP: $M=4.96$, $SD=4.1$.

In order to test our *Hypothesis 1: better effect on spatial knowledge acquisition with the FWIP than with the JS*, we conducted independent-samples t-test (one-tailed) at 95% confidence level to compare the means on the penalty scores of the FWIP and the JS. There was a significantly better

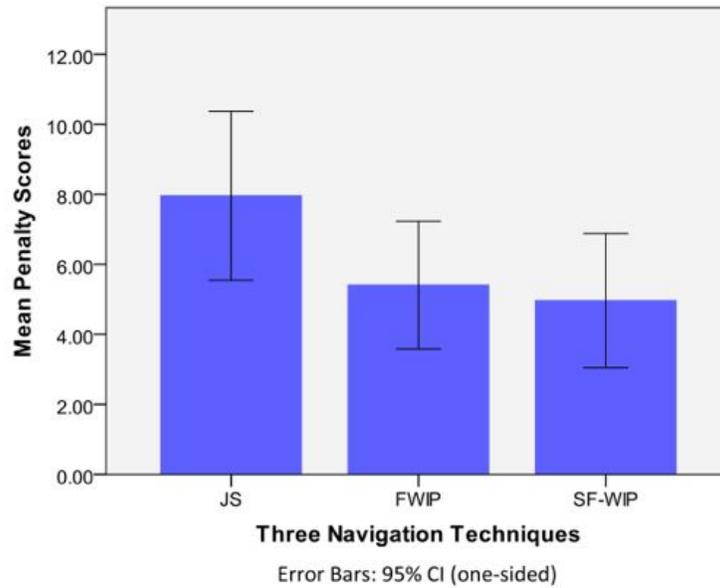


Figure 5.6: Mean penalty scores from the (red) route replication task, when the penalty weight for missing segments is 1.

effect on route knowledge acquisition in the FWIP, $t(38) = -1.8, p < .05 (= .04)$ when P_{ms} is $\frac{1}{2}$, and $t(38) = -1.77, p < .05 (= .043)$ when P_{ms} is 1. We also conducted another independent-samples t-test (one-tailed) to compare the means on the penalty scores of JS vs. SF-WIP with the similar hypothesis as *Hypothesis 1*, i.e., better effect on spatial knowledge acquisition with SF-WIP than with JS. The result showed the significantly better effect on route knowledge acquisition in the SF-WIP, compared with the JS. The results are summarized in Table 5.2.

Table 5.2: Results of t-test to compare the penalty scores in *FWIP* vs. *JS*, and *SF-WIP* vs. *JS*; two penalty-weight values (i.e., 0.5 and 1) are used for missing segments.

Weight Value	FWIP vs. JS	SF-WIP vs. JS
0.5	$p < 0.05 (= 0.041)$	$p < 0.05 (= 0.049)$
1	$p < 0.05 (= 0.042)$	$p < 0.05 (= 0.031)$

In order to test our *Hypothesis 2: no significant difference on spatial knowledge acquisition between FWIP and SF-WIP*, we conducted an independent-samples t-test (two-tailed) at 95% con-

confidence level to compare the means on the penalty scores of FWIP and SF-WIP. There was no significant effect on route knowledge acquisition of FWIP, compared with SF-WIP, in the both cases with two P_{ms} values.

We noticed that our measured penalty scores could be affected by the task-completion time as well as different NavTechs (i.e., action-transferred vs. non-action-based) because different NavTechs inevitably provided different navigation speeds although our experiment design was based on the time constraint (i.e., 4 minutes). Since the t-test cannot control the ‘time’ factor, we conducted another statistical test, analysis of covariance (ANCOVA) with the ‘time’ as a covariate, i.e., penalty scores as dependent variable, navigation techniques as independent variable, task-completion time for route replication task as covariate were controlled in the ANCOVA test. The results of the ANCOVA test showed that there was a significantly different effect of three NavTechs on the penalty scores of the route knowledge replication task (i.e., accuracy of route knowledge acquired) after the possible bias of ‘time’ was eliminated (or controlled); $F(2, 56) = 5.252, p = .008$, when P_{ms} is 1. The results including other pairwise comparisons are summarized in Table 5.3.

Table 5.3: Pairwise comparisons of ANCOVA test with the ‘time’ covariate to compare the penalty scores; two penalty-weight values (i.e., 0.5 and 1) are used for missing segments.

Weight Value	FWIP vs. JS	FWIP vs. SF-WIP	SF-WIP vs. JS
0.5	$p < .05(= .000)$	$p > .05(= .546)$	$p < .05(= .002)$
1	$p < .05(= .006)$	$p > .05(= .903)$	$p < .05(= .007)$

As shown in Table 5.3, the results of ANCOVA test are compatible to the results of t-test, but show more strong trends to support our hypotheses after removing the effect of time (covariate) on penalty scores.

In summary, both statistical tests (t-test and ANCOVA test) support our two hypotheses – the FWIP shows the effect on spatial knowledge acquisition better than the JS (*Hypothesis 1*) while the FWIP and the SF-WIP have no significant difference on spatial knowledge acquisition (*Hypothesis 2*). Consequently the results support our design approach that the action-transferred NavTech (e.g.,

FWIP) is effective for spatial learning as much as the walking-like NavTech (i.e., original action-based NavTech).

Survey Knowledge Acquisition

Based on the collected data from the maze-map based multiple-choice question, Table 5.4 shows how many participants of three groups selected the correct answer.

Table 5.4: The number of participants who provided the correct answers to the multiple-choice question for survey knowledge acquisition

NavTech group	#of users who chose the correct answer
FWIP	12
JS	6
SF-WIP	9

In order to evaluate the performance of participants on survey knowledge acquisition with this result, we used the same evaluation hypothesis described in §4.4.2:

Without survey knowledge, the probability to randomly choose the correct answer is $\frac{1}{6}$, while the probability for the wrong answer is $\frac{5}{6}$, when the maze-map based multiple-choice question has six items. If the probability of the correct answers in any NavTech group is found statistically outperforming over $\frac{1}{6}$, we can conclude whether the NavTech group's users acquired survey knowledge after the maze experience.

We used the same statistical test described in §4.4.2, i.e., one-sample chi-square goodness-of-fit-test and a generalized Fisher's exact test. The results were presented in Table 5.5.

In Table 5.5, the larger value of χ^2 means that more number of participants with the given NavTech acquired survey knowledge. As Table 5.5 shows, there is enough evidence (at the $\alpha = 0.05$ level of

Table 5.5: Results of chi-square(χ^2) goodness-of-fit-test indicate that participants with the FWIP and the SF-WIP but not with the JS NavTechs acquired survey knowledge

NavTech group	Chi-Square(χ^2)	p-value	p-value (with the generalized Fisher's exact test)
FWIP	26.955	< .05(= 0.000)	< .05(= 0.000)
JS	2.543	> .05(= 0.111)	> .05(= 0.128)
SF-WIP	11.514	< .05(= 0.001)	< .05(= 0.003)

significance) to conclude that the participants with the FWIP and the SF-WIP NavTechs acquired survey knowledge, whereas there is not enough evidence that the participants with the JS acquired survey knowledge.

Subjective Sense of Presence

In order to examine the subjective sense of presence, Presence Questionnaire (PQ) [121] was used, which has three categories; *Involvement*, *Adaptation/Immersion*, and *Interface Quality*. Because three categories of PQ have different numbers of items, i.e., 56, 49 and 21 items, respectively, we normalized the raw scores of PQ. Figure 5.7 shows the means of the normalized scores of PQ in three NavTechs based on three categories. We compared the normalized scores of PQ using one-way ANOVA (at the $\alpha = 0.05$ level of significance) that had one between-participants factor of three NavTech groups. The results showed that there were significant differences on the participants' sense of presence in all three categories; *Involvement*: $F(2, 57) = 4.397, p = 0.017$; *Adaptation/Immersion*: $F(2, 57) = 5.138, p = 0.009$; *Interface Quality*: $F(2, 57) = 5.447, p = 0.007$.

Tukey HSD post-hocs showed that significantly higher sense of presence was found in the SF-WIP group than in the JS group to all three categories; *Involvement*: $p = 0.018$; *Adaptation/Immersion*: $p = 0.006$; *Interface Quality*: $p = 0.044$, while significantly higher sense of presence was found in the SF-WIP group than in the FWIP group only for one category; *Interface Quality*: $p = 0.008$. There were no significant differences found in the other pairwise comparisons.

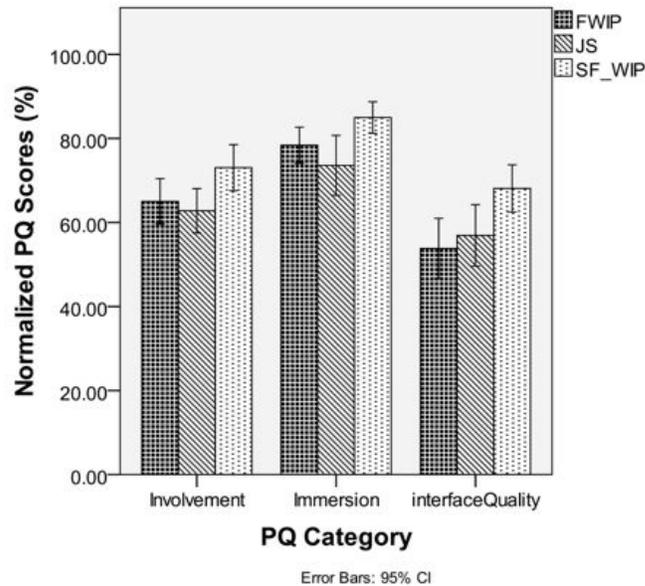


Figure 5.7: Normalized scores of Presence Questionnaire (PQ). In all three categories, the SF-WIP NavTech showed the higher sense of presence, compared to the FWIP and the JS.

5.2.3 Discussion

In our between-subjects design, the study results showed that the participants in the FWIP and the SF-WIP groups acquired more accurate route and survey knowledge, compared to those in the JS group. Thus, the results support our two hypotheses; (1) the action-transferred NavTech (FWIP) supports the participants to more effectively acquire spatial knowledge, compared to a wand-and-joystick common NavTech (JS) and (2) there is no significantly different effect between an action-transferred NavTech (FWIP) and the original action-based NavTech (SF-WIP) on spatial knowledge acquisition.

In the remaining parts, we discuss our observations and experiences from our study in this chapter.

Spatial Learning Supported by Experiential Learning Theory

We asked all participants to take the route replication task for all three pre-defined routes (red, blue and yellow routes in order). However, we only used the data from the first route replication

task for our evaluation assessing route knowledge because we observed that all participants in three NavTech groups developed their spatial knowledge more accurately with more navigation experiences in the maze. Since the single maze was used and some parts of three routes in the maze overlap, the rest of route replication tasks on blue and yellow routes must be influenced by the prior route experiences. As shown in Figure 5.8, as the participants in all three NavTech groups had more route navigation tasks (red, blue and yellow in order), the penalty scores were decreased, meaning that route knowledge of a participant was acquired more accurately.

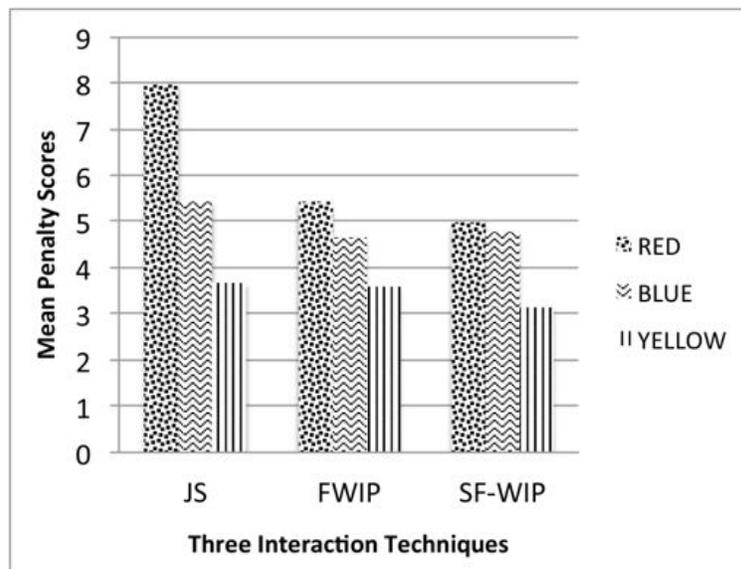


Figure 5.8: Mean penalty scores from the route replication task on three routes, when the penalty weight for missing segments is 1.

As Table 5.6 shows that the means of penalty scores in three NavTech groups at the yellow route replication task are much smaller than at the red route replication task for both penalty weight values ‘1’ and ‘ $\frac{1}{2}$ ’. Even the success rates of the participants in three NavTech groups seemed getting better as the participants had more experiences with the maze (Figure 5.9) although the success rates are not statistically confirmed due to the small sample size. These observations on our data analysis support our theoretical reasoning in (spatial) learning, which suggests that people would develop more accurate route knowledge by having more experiences in an environment – *experiential learning theory* [49].

Table 5.6: Mean penalty scores from the route replication task on three routes, when the penalty weights for missing segments are 0.5 and 1, respectively. As route knowledge is being developed with more experiences, the penalty scores of more participants can be zero. Hence, SD can be greater than Mean.

Missing Penalty Weight Value	NavTech group	Red (1st) route	Blue (2nd) route	Yellow (3rd) route
0.5	JS	$M=5.51, SD=4.1$	$M=3.9, SD=3.15$	$M=2.59, SD=3.78$
	FWIP	$M=3.56, SD=2.6$	$M=3.12, SD=2.38$	$M=2.6, SD=3.12$
	SF-WIP	$M=3.44, SD=2.86$	$M=3.89, SD=3.84$	$M=2.27, SD=2.7$
1	JS	$M=7.96, SD=5.15$	$M=5.41, SD=3.81$	$M=3.66, SD=4.62$
	FWIP	$M=5.41, SD=3.9$	$M=4.67, SD=3.37$	$M=3.57, SD=4.16$
	SF-WIP	$M=4.96, SD=4.1$	$M=4.79, SD=4.86$	$M=3.14, SD=3.78$

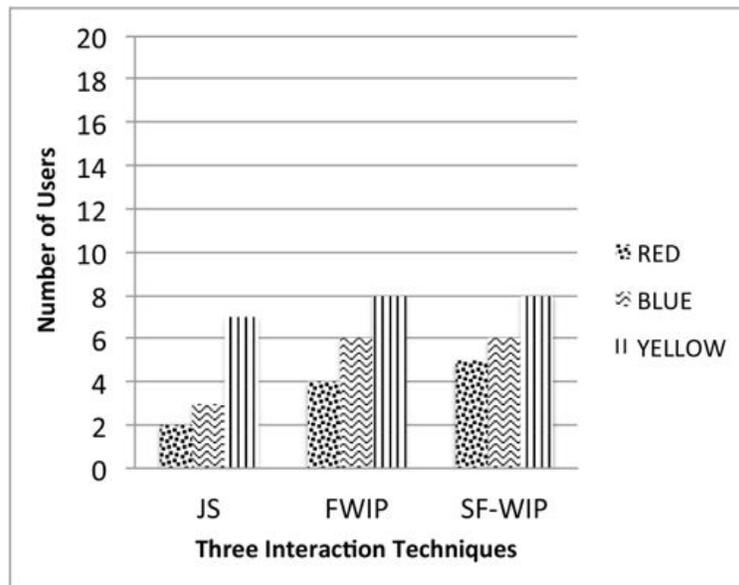


Figure 5.9: The number of users who successfully finished the route replication tasks.

Correlation between Time and Accuracy of Route Knowledge Acquired

Section §5.2.2 shows interesting results implying that the accuracy of route knowledge was more significantly affected by the different NavTechs after the ‘time’ factor was controlled. That said,

that action-transferred NavTech more effectively supported route knowledge acquisition, compared to the non-walking and common NavTech. We conducted another statistical test, Pearson’s correlation test to examine the correlation between time and accuracy of route knowledge. The results are summarized in Table 5.7. While it is generally assumed that more time would result in better spatial learning, our Pearson’s r-test shows that more time taken for completing route replication task can result in less accurate route knowledge (*inverse correlation*). The results may suggest that spatial learning effect would not be necessarily improved by slow speed (or large amount of time) but rather improved by effective action (over-learned) and individuals’ comfortable speed to perform the action.

Table 5.7: Pearson’s correlation test (*r – test*): positive correlation of time and penalty scores (inverse correlation of time and accuracy of route knowledge); two penalty-weight values (i.e., 0.5 and 1) are used for missing segments.

Weight Value	FWIP	JS	SF-WIP
0.5	$r = .543, p = .013$	$r = .792, p = .000$	$r = .467, p = .038$
1	$r = .435, p = .056$	$r = .607, p = .005$	$r = .246, p = .295$

Effect on Intolerable Cyber-Sickness

An important observation was made from the participants with the JS. Seven participants using the JS withdrew from the experiment due to intolerable cyber-sickness (also known as *motion sickness*), including nausea and dizziness. Two participants had to quit the experiment task immediately after the test session started due to cyber-sickness. Three participants barely finished up to the first sub-session (i.e., red-route navigation) and then quit. The remaining two participants almost finished up to the third sub-session but could not start the last sub-session and quit. We statistically tested the different proportions of cyber-sickness in three NavTech groups. Although no significant different proportion of cyber-sickness was found between the JS and the FWIP ($\chi^2(1, N = 51) = 2.71, p = .1$), there was a strong trend that the JS caused intolerable cyber-sickness,

compared to the SF-WIP ($\chi^2(1, N = 48) = 3.81, p = .051$).

The more severe symptoms were observed from the participants in our informal pilot study with less complicated tasks, using the modified JS (JS_{pilot}) where the wand device was fixed on a table and only the joystick was operated by a participant. With the JS_{pilot} , six out of eleven participants (almost every other participant) withdrew from the experiment due to cyber-sickness (in particular, nausea and/or dizziness). While the JS allowed participants to physically move their body, e.g., turning the body in place or swinging the arm with holding the wand by the hand, the participants using the JS_{pilot} NavTech were not allowed to physically move but required to stand at the table. This setup of the JS_{pilot} is identical to that of the FWIP. Hence, we shall conjecture that action-transferred NavTech may provide another important benefit in terms of diminishing cyber-sickness and enabling longer exposure of people to immersive VEs, compared to the JS (i.e., common NavTech in VEs).

If we consider that immersive VEs can be realized in our every day lives through consumer products, such as 3D TVs, soon enough, this cyber-sickness can be a critical issue in the real world. Further research is needed to provide suitable 3D interaction techniques for 3D TVs since cyber-sickness can be emerged with 3D TVs.

Effect on Sense of Presence

Although the sense of presence is an important factor to assess the quality of the subjective experiences in immersive VEs, there were only few empirical studies that investigated the effect of different NavTechs on the sense of presence since the effectiveness of walking-like NavTechs has already been demonstrated in [90, 104]. In addition, there is no theory supporting that action is closely related to the sense of presence. Hence, we were not able to expect the effect of the transferred action on the sense of presence.

The results of the subjective sense of presence using PQ (§5.2.2) were quite interesting. The comparisons of the SF-WIP and the JS groups in three categories (*Involvement, Adaptation/Immersion*

and *Interface Quality*) of PQ showed the consistent results as [90] and [104], i.e., walking-like NavTechs enhanced the sense of presence significantly higher than the wand-joystick common NavTech. However, in the comparisons of the SF-WIP and the FWIP, only one category, *Interface Quality*, of PQ showed that the SF-WIP significantly enhanced the sense of presence, compared to the FWIP. There were no significant differences found in the other comparisons, i.e., FWIP vs. JS in three categories and FWIP vs. SF-WIP in *Involvement* and *Adaptation/Immersion*. From this one study, it may be inappropriate to claim that the sense of presence is influenced by the transferred action as well as the original action because there were no significant differences found in the comparison of the FWIP and the JS to the three categories of PQ. However, it would be an interesting research direction to investigate the effect of transferred action on the sense of presence.

Abstract Form as Control Similarity

As indicated in our *Hypothesis 2*, the transferred action and the original action can have the shared representation, i.e., same abstract form, stored in our brain. Since the abstract form refers to “motor pattern” [81], the motor pattern should be produced by the transferred action as well as the original action. However, it is not possible to see the actual motor pattern encoded in our brain, but the motor pattern can be only conjectured from the original action.

On the other hand, the similarity of the motor pattern in the transferred and original actions may be explained as the similarity of control. McMahan [58] attempts to analyze the motor pattern (of interaction techniques) divided into several components, in the “Control Symmetry” category, which is a part of the Framework for Interaction Fidelity Analysis (FIFA). Although the purpose of the FIFA explains the level of interaction fidelity¹, the FIFA’s control symmetry can be useful to explain how much the transferred action is closed to the original action in terms of the similarity of the motor pattern.

According to the FIFA, control symmetry is explained by three components, *Dimensional Sym-*

¹“the objective degree of exactness with which real-world interactions can be reproduced in an interactive system” [58]

metry, Transfer Function Symmetry and *Termination Symmetry*. By the definitions of these three components [58], it can be considered that the FWIP produces relatively high control similarity to the ‘walking’ action in terms of two-dimensional control and same termination control. However, the FWIP produces relatively moderate similarity to the ‘walking’ action for *Transfer Function Symmetry* because the ‘walking’ action is based on “position-to-position” control while the FWIP is based on “movement-to-position” control. Hence, the motor pattern of the FWIP seems closer to that of “walking-in-place” [58] rather than ‘walking’, according to control symmetry of the FIFA. However, we found that there can be a missing component in control symmetry, which may be critical. As we explained, the FWIP can control different variations of walking, such as “walking forward”, “walking backward” and “walking sideways” and “turning in place”. “Walking backward” and “walking sideways” cannot be controlled by “walking in place” itself because “walking in place” has no directional movement. Hence, it would be suggested to add another component such as “Movement Direction Symmetry”, to the control symmetry category in the FIFA.

In terms of control similarity, we can assume that the FWIP and walking have very similar control to the motor pattern, supporting that the FWIP is the transferred action from the original ‘walking’ action.

5.3 Suggested Guidance

The concept of the action-transferred design approach is based on a broader concept grounded in the motor equivalence theory that we can replace one biological effector (i.e., body part) with another and retain the associated natural and learned capabilities. In our empirical study with the FWIP technique, we demonstrated that spatial learning abilities such as route and survey knowledge acquisition can be transferred when bipedal walking action is replaced with finger-based walking action.

This has broader implications for designing interaction techniques, not limited to NavTechs, where it is desirable to replace the biological effector(s) with the other(s). For example, action-transfer

would be needed when the user has a disability that compromises the use of a body part. Suppose that a person cannot use head-movement due to neck-pain or neck-injury. Since head-movement is known as a useful action for recognizing objects, we may want to design an interaction technique by transferring the head motion to the fist (with the wrist). Then we would expect the similar effect of the action-transferred interaction technique on object-recognition. Another example as a need of action-transfer is when a replacement is desired for fatigue or convenience reasons (as argued in this dissertation). We can abstract our principles to give insight into how such a design of action transfer may be achieved.

The first step is to find an abstract form. For this, we first need to identify a specific natural action (e.g., walking, grabbing or throwing) to be transferred. Its effectiveness for a certain goal should be known. Then by observing the action, the original action can be decomposed into its constituent unit-actions as necessary. These unit-actions would be mapped to the target effector(s). The key criterion for this decomposition is that all unit-actions must contain a common action. Finally, we can determine a common form contained in all unit-actions. We assume that this common form is considered as the abstract form of the original action.

The second step is to determine what effector(s) would be good for mapping the abstract form. This decision can be made by considering several factors, such as the purpose of a target application domain or the type of original action. For example, if we develop an interaction technique by mapping 'writing' action for people with limited hand or arm use, arm or hand would be excluded as a target effector. If the design purpose is focused on reducing any body fatigue and enhancing convenient and efficient use, small muscle groups (e.g., fingers or thumbs) would be the best candidates [124]. If the original action is performed by a pair of two effectors, any single effector system would be excluded.

Finally, we can design an interaction technique by mapping the abstract form to the target effectors. Based on the unit-actions, the interaction technique can have some variations with one-to-one correspondence or with fewer number of unit-actions because some unit-actions can be grouped as a single variation of the interaction technique.

The implementation of the produced action-transferred interaction technique would be dependent on capabilities and availability of contemporary technologies. Also, we need to test the implemented interaction technique by using user studies, including usability test and comparative studies. However, we do not need to go through all possible factor-combinations in the user studies because our design guidance suggests anticipated effects from the action-transferred interaction technique on the application-specific goal.

5.4 Chapter Summary

In this chapter, we presented how we can develop an action-transferred navigation technique (NavTech) by using “finger-walking” as common intuition. In order to properly provide feasible FWIP technique for navigation in VEs, we went through several iterations of design and implementation to refine our FWIP.

Before formally evaluating our action-transferred NavTech, we conducted a preliminary comparative user study employing the similar experiment design as presented in [69] because it was the only study to investigate route and survey knowledge acquisition separately.

Our preliminary study [45] showed that the better route knowledge acquisition was supported by the FWIP than the JS. This preliminary study results were very promising because it was initially demonstrated that our action-transferred design approach can be effective for spatial learning. However, we found some limitations (§5.1.3), such as insufficient experience about the environment and inappropriate method for assessing survey knowledge, in the preliminary experiment design adopted from [69] and addressed these limitations when designing our formal comparative study.

Our comparative user study successfully demonstrated the effect of the FWIP on both route and survey knowledge acquisition (i.e., spatial learning), compared to the wand-and-joystick based NavTech (JS), while showing the similar spatial learning effect to that of the sensor-fusion walking-in-place (SF-WIP) NavTech.

Thus, we provided a possible answer to our key research question: *how can we design a convenient NavTech providing effective spatial benefits with reduced whole-body fatigue, controlled space size, and/or system-configuration complexity?*, by presenting the details of design and implementation of the FWIP, which is the NavTech based on lightweight action (using small-muscle groups) transferred from the original ‘walking’ action, and by demonstrating the effectiveness of the FWIP for spatial learning in our empirical study. Although our conclusion is drawn from the empirical study using one transferred action based NaveTech, i.e., FWIP, and is therefore not direct evidence at the neural level, it should be notable that our action-transferred design approach for effective spatial learning is strongly supported by the theories that have been demonstrated by a number of studies.

In addition, we observed that the participants using the JS generated more severe cyber-sickness, compared with the FWIP and the SF-WIP participants. Although we could not confirm this observation statistically, it can be an important research topic. Especially, this observation is important considering that the FWIP was performed without allowing any physical body-movement at all (except for fingers) while the JS allowed some physical body movements (e.g., body-turn or walking around within the limited space). It may suggest that cyber-sickness can be diminished by transferred action without physical movement.

In order to explain the similarity of the original action (walking) and transferred action (FWIP), we used the “Control Symmetry” category, which is a part of the Framework for Interaction Fidelity Analysis (FIFA). Two components, dimensional control and termination control, of control symmetry are very similar while transfer function control is moderately similar in walking and the FWIP. We suggested adding another component, such as “movement direction symmetry”, to the control symmetry category because the FWIP has another similarity with walking in terms of the movement direction, e.g., “walking backward” or “walking sideways”. As shown in this explanation using the FIFA’s control symmetry, the FWIP and walking have very similar control to the motor pattern.

Then we suggested a guidance how our new design approach using the action-transfer concept can

be applied to developing other new interaction techniques, show a possible systematic procedure to develop action-transferred interaction techniques when the effectiveness of original actions is known. In order to provide the usefulness of this systematic procedure to design new action-transferred interaction techniques, there should be further investigation followed.

Chapter 6

Exploring The Effect of Transferred Action on Action-Dependent Perception

In the previous chapter 5, we demonstrated that our action-transferred approach using the finger-walking-in-place (FWIP) navigation technique (NavTech) was more effective in route and survey knowledge acquisition, compared with a non-walking common NavTech (based on a wand-and-joystick device) in virtual environments (VEs). The study in Chapter 5 suggested that spatial learning effect is still maintained by the transferred-action coupled with perception that was dependent on the original action.

As we provided our reasoning in Chapter 3, perception and action not only play central roles for spatial learning but also inform each other (i.e., tight coupling). If this coupling is not dependent on the biological effectors, we can expect that our perceptual ability dependent on a specific action is maintained by its transferred action. However, the study in Chapter 5 did not directly support that our perceptual ability dependent on the original action is still maintained by the transferred action.

In this chapter, we present another user study to explore if there is any effect of the transferred action on the perception that would be coupled with the original action. Specifically speaking,

we explore if there is any connection between the transferred action and the perception when the perception is coupled with the original action (walking). We name this study as “PerceptStudy” to avoid any confusion with our previous user studies that were based on maze navigation. In PerceptStudy, our exploration focuses on three different types of perception, i.e., size, shape and distance perception, of given 3-D objects in VEs.

(Blind) ‘walking’ has been used as a common metric to assess the egocentric distance perception since it has been introduced by Loomis *et al.* [55], there are few studies to demonstrate that walking-like NavTechs are effective for distance (or depth) perception [56, 59, 102, 114]. However, we can assume that walking-like NavTechs should be effective for distance perception because several studies involving spatial navigation tasks demonstrated that walking-like NavTechs support users to acquire more accurate spatial knowledge (§2.3) that would include accurate distance perception, suggesting *coupling of walking action and distance perception*.

On the other hand, it is yet unknown whether the ‘walking’ action is coupled with either size or shape perception. However, we may conjecture that size and shape perception on objects would relate to manipulation and observation within one’s arm reach, and therefore size and shape perception may be better facilitated by head and eye movements as well as manipulation by hand rather than the whole-body movement such as walking. Thus, we expect that distance perception would be positively influenced by walking-like NavTechs while size or shape perception would not be affected by walking-like NavTechs as much as distance perception.

PerceptStudy is newly designed to investigate the effect of the action-transferred NavTech, i.e., FWIP, compared with the common NavTech (i.e., wand-and-joystick based NavTech (JS)), on the perceptual ability (e.g., distance perception) dependent on the original action (i.e., walking).

6.1 Overview of PerceptStudy Design

It was very challengeable to design the experiment tasks for PerceptStudy because it is very hard to find any literature related to investigating the effect of different NavTechs on perceptual ability

on 3-D objects in VEs. Hence, we need to take a few steps toward designing our own experiment.

Firstly, we consider eliminating as much bias as possible, such as cultural aspect, texture-pattern, color, arrangement and configuration-complexity of objects. These cultural, spatial and visual cues of 3-D objects can affect the way people perceive size, shape and distance of objects [57, 87]. Hence, we need to minimize the amount of visual cues that can affect each other.

Secondly, we consider how spatially close the objects are presented to users. It seems obvious that people better perceive spatial aspects or visual features of an object within the arm's reach, compared to beyond the arm's reach [4]. In order to avoid the possibility of "ceiling effect", which is referred when performance on perceptual ability is nearly perfect, we need to provide a spatial constraint between the observer and the objects, so that users are not allowed to observe the objects within the arm's reach.

Thirdly, we consider designing the experiment tasks to objectively evaluate the perceptual ability of a user with a given NavTech. The common tasks for measuring perceptual ability on objects include different spatial judgment tasks, such as farther, nearer, smaller, bigger, higher, lower and so forth from a fixed viewpoint [63] or absolute distance estimate [4]. However, these tasks are not appropriate to investigate the perceptual performance of two different active navigation modes because users can continuously correct their perceptual judgments by taking different perspectives as much as possible to accurately judge the size, shape and distance of objects. For another example, the absolute distance estimate should contain another ability regarding unit-conversion inducing possible confounded results. In addition, we need to consider two different human abilities regarding memory and perception that can affect each other. For example, we may show one object to a user at the first scene and ask the user to find the same object in the next scene, in terms of size, shape and distance. Is the task for testing the user's memory or perceptual ability? Hence, our experiment tasks need to be designed to minimize the influence of memory ability on perceptual ability performance.

Finally, we need to determine the evaluation metrics to assess the perception performance on the designed experiment tasks. Based on the considerations described above, our suggested experiment

design is as follows,

- *Virtual Objects*: Considering any bias of cultural aspect, color, texture and complexity of object configuration, we decided to provide geometry-like objects with a solid color. However, the objects should not be too abstract because the abstract shape may also induce any cultural bias [87]. Hence, we decided to adopt molecule-like objects with irregular angles, with which we can also easily manipulate the configurational complexity of objects.
- *Placement of Objects*: If we allow users to move through the objects, there can be very little difference in the task performance because everyone would approach to the objects as close as possible and observe the objects. Instead we decided to place an object inside a transparent glass box with collision, so that the users can see through the objects but cannot go through the objects, i.e., they cannot go through the transparent glass boxes.
- *Perception Tasks*: In order to minimize the possibility of memory effect to assess the perceptual ability to judge the size, shape and distance of objects, we first devised a task in which several objects are presented to a user and the user should judge how much one objects is similar to the other objects in terms of size, shape and distance. Based on our observation in the informal pilot study, we observed that the individuals could have different calibration grounds to judge the size, shape and distance of objects, so that the variation of the collected data was very large. For example, one user can judge the size of Object A 4 times bigger than Object B while the other user can judge the size of Object A 1.5 times bigger than Object B, when the sizes of two Objects A and B are same. If the other users judge the size of Object A as 1.2 times, 3 times, 2 times and so forth bigger than the size of Object B, it would be very hard to determine assessing the perceptual ability of participants in different NavTech groups. Hence, instead of measuring the scaled data (e.g., 3 times bigger size or 20% different shape), we decided to provide several multiple-choice tasks. Per task, three objects will be presented to the user. The user will observe one of three objects, which is arbitrarily chosen by the experimenter. After a certain amount of time for observation, the user will be asked to find which object has identical size, shape or distance as the first observed object.

Thus, our designed tasks may be able to minimize the memory effect as well as the issue of individuals' different calibration.

- *Evaluation*: The number of multiple-choice tasks will be determined considering the total experiment time. Also, we need to determine how long the users are allowed to observe the objects per task. The time taken per task should not be too long or too short. We decided the appropriate number of tasks and the completion time taken per task by performing a pilot study and by interactively interviewing the users during the tasks. Details are described in the subsequent sections.

In addition, we add another NavTech condition, the modified JS technique removing the wand's orientation control (i.e., body-turn is not allowed), so that users are only allowed to control the joystick for moving around objects in the virtual space. Since the modified JS condition is almost identical to the condition of the FWIP, both of which do not allow physical body-turn, we are able to eliminate the possible confound (e.g., physical body-controlled navigation) from the JS (§4.2.1). Thus, we are able to provide the equal experiment condition to compare the task performance of the action-transferred NavTech (FWIP) and the non-walking NavTech (JS).

Note that we excluded the modified JS condition from our maze-based studies because we observed the high-dropout rate (over 50 %) due to intolerable cyber-sickness in the pilot study (detailed in §5.2.3). It was observed that the maze-based navigation tasks required participants to rotate and translate a lot for wayfinding and learning spatial layout of the maze. Hence, we did not want to take the risk of the possible high-dropout rate for our previous maze-based studies. However, in PerceptStudy designed to examine one's perceptual ability on 3-D objects, we assume that cyber-sickness would not be severe as much as the maze-based studies because users need not to rotate and translate as many times as in the maze-based navigation tasks. We expect that users observe objects precisely focusing on the three types of perception, i.e., size, shape and distance of objects, while they stay at a position during observation without continuously rotating and moving. Although it is yet unknown what factors exactly cause cyber-sickness, it must be related to the users' movement in VEs [53]. Hence, cyber-sickness may be more lightly caused even with the

modified JS NavTech in PerceptStudy than in our maze-based pilot study.

6.2 Explorative Study: PerceptStudy

For PerceptStudy, we hypothesize that *there will be better performance in distance perception with the FWIP than with the JS, while there will be no difference on size and shape perception performance in the FWIP and the JS NavTechs.*

We used a between-subjects factor of NavTechs and a within-subjects factor of the perception tasks. Based on the overview of our PerceptStudy design, our experiment was configured as illustrated in Figure 6.1. We provided three NavTechs, a finger-walking-in-place (FWIP) implemented on an Apple's iPad (Figure 6.2), a wand-and-joystick (JS) navigation technique (Figure 6.3) and the modified JS with the wand fixed on the top of a table (JS_{table}) as shown in Figure 6.4. Three types of perception, i.e., size, shape and distance between objects, are explored in this study.

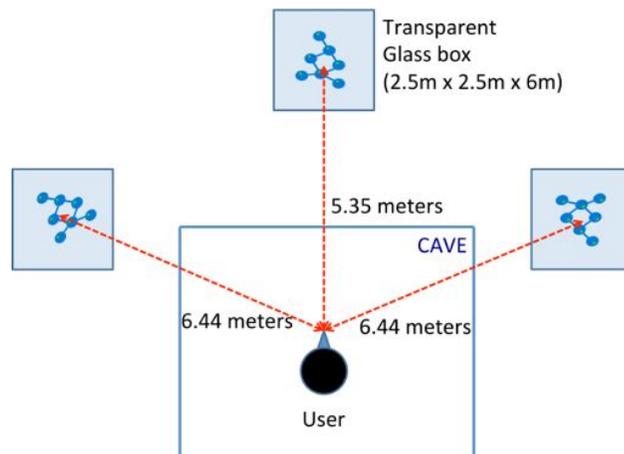


Figure 6.1: Top-view of the experiment setup with three objects in three transparent glass boxes.

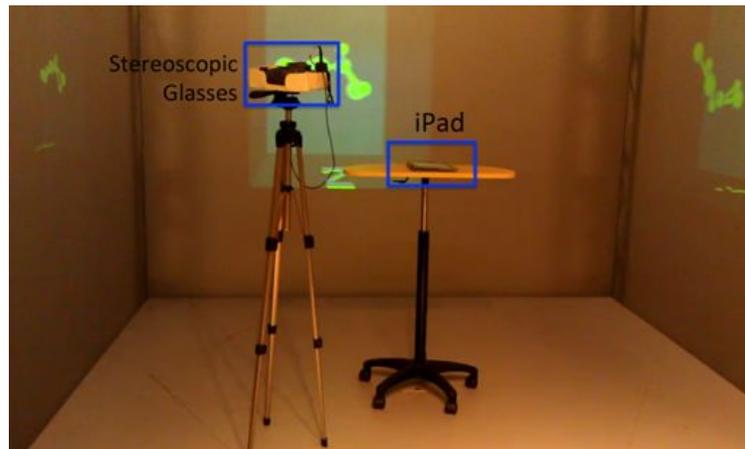


Figure 6.2: FWIP technique setup with the iPad fixed on the table.

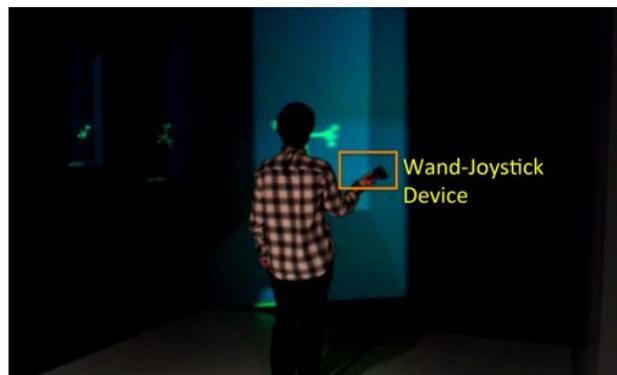


Figure 6.3: JS technique setup which is a common setup in virtual environments.

6.2.1 Method

Virtual Environment System

We used a Linux-based CAVE system including three 10' by 10' walls and a floor stereo projection screens, each with 1920×1920 resolution, and the Intersense IS-900 VET tracking system for a head tracker, attached on the shutter glasses. The display refresh rate is 60Hz. Since this tracking system is provided by a dedicated wireless infrastructure, the refresh rate of the tracking system is constant (120Hz).

In order to facilitate the experiment with several tasks, we provided a remote-control application on



Figure 6.4: Modified JS technique (JS_{table}) setup: a wand and joystick navigation technique with the wand fixed on the table.

an iPad. Hence, an experimenter was able to control the experiment tasks while the experimenter is giving some instructions to participants in a training phase and a testing phase. Moreover, the experimenter was able to continuously observe each participant's behavior during the entire experiment without any interruption.

Design of Virtual Objects

As described in the overview of our PerceptStudy design, we designed molecule-like objects so that we were able to easily design the virtual objects by changing the size, shape and distance aspects of components of each molecule-like object. We placed each object inside a transparent glass box, so that participants were able to see through the object but not move through the transparent glass box. We used '1', '2' and '3' number-objects placed on the bottom of each transparent glass box to indicate each object during the experiment. These number-objects must not create any visual barrier during observation of the objects. Our virtual space with three transparent glass boxes and three objects is viewed to participants as shown in Figure 6.5.

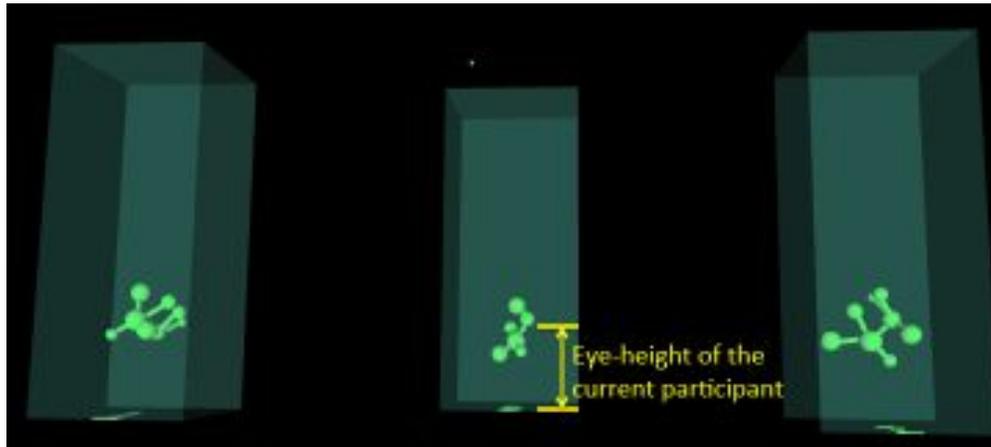


Figure 6.5: Three molecule-like objects. Each object is placed at the eye height of each participant inside a transparent glass box.

Pre-Experiment Spatial Ability Test

Spatial orientation ability was measured with the Cube Comparison test [21] at the beginning of the experiment, which required the participants to mentally rotate an object about its center. In each item, two drawings of a cube were presented; the participant was asked to compare the orientation of the faces on each cube to determine if the two cubes were the same or different. This Cube Comparison test consist of 42 items. All participants took the test with the first 21 items within 3 minutes and finished the rest 21 items within 3 minutes after a short break. After each participant finished the test, we recorded the answers of the participant on an Excel data sheet to immediately get the test-result, so that we were able to evenly distribute the participants into three NavTechs groups before the participant performed the experiment tasks.

Participants

We recruited participants who have no problem distinguishing colors and who have no disability from a recruiting system maintained by Psychology Department at Virginia Tech. All participants were randomly assigned to three groups according to the spatial orientation ability results of participants, being balanced across the groups. All participants also provided their experienced level

with a joystick and touch-based interfaces (e.g., smartphone) using a seven-point Likert scale. The eye-height of each participant was measured from the ground before starting the experiment tasks in the VE. The measured eye-height was used to place the virtual objects inside the transparent glass box.

Twenty participants per group were expected. Eleven participants withdrew due to severe cyber-sickness (e.g., nausea or dizziness), three (female) from the JS group and eight (female) from the (JS_{table}) group, but no one withdrew from the FWIP. The data of one (male) participant in the FWIP group was excluded from our data analysis because he failed to distinguish the different colors to perform the distance perception tasks (§6.2.1). He actually self-reported as color blind but only for red and green, and therefore successfully passed our training session including the task distinguishing different colors (i.e., yellowish green and lime colors (§6.2.1)). However, during the testing phase, he was not able to distinguish two colors as the objects were getting more complicated. Hence, we recruited additional participants to collect the data of twenty participants per group, who completed the experiment tasks.

Since the high dropout rate (8 out of 21) was observed from the JS_{table} group, we stopped recruiting more participants for the JS_{table} when we had twenty one participants for the JS_{table} group. Details are discussed in §6.2.3. Thus, forty participants' data of the FWIP and the JS groups were used for our data analysis. Table 6.1 shows the demographic data of the participants who successfully finished the experiment tasks.

Table 6.1: Summary of demographic data for the participants who successfully completed the experiment tasks.

NavTechs	Age	Gender	Joystick Exp.	Touch Exp.	Cube Comp. Test
FWIP	$M = 19.7$	Female:8	$M = 2.65$	$M = 3.9$	$M = 21.35$
	$SD = 1.45$	Male:12	$SD = 1.9$	$SD = 1.9$	$SD = 5.7$
JS	$M = 19.75$	Female:8	$M = 2.07$	$M = 3.57$	$M = 21.75$
	$SD = 2.71$	Male:12	$SD = 1.66$	$SD = 2.3$	$SD = 7.34$

Procedure

Training Phase

All participants went through two training sessions. The first training session was designed for the participants to get familiar with a given interface (i.e., either FWIP or JS) by moving around the big boxes in the black background (Figure 6.6). At the beginning of the second training session, we prepared one task that required participants correctly distinguished different colors, which were related to distance perception task. During the second training session, the participants were trained to get familiar with how to perform the experiment tasks for size, shape and distance perception. Three tasks were provided for the three types of perception, i.e., size, shape and distance in the second training session. Each participant was required to finish each task (refer to the *Testing Phase* section for details) within 3 minutes.

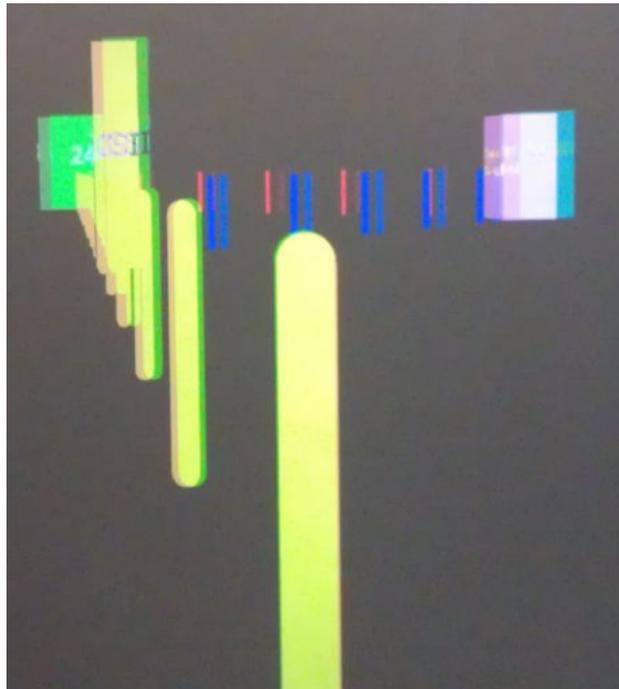


Figure 6.6: The first training session: all participants reach yellow, pink and green boxes guided yellow, blue and red poles.

The two training sessions lasted approximately 30 minutes including the experimenter's instruc-

tions and a participant’s inquiries, if any. Before moving on the testing phase, the experimenter checked with the participants whether they clearly understood how to use the given interface and how to perform the experiment tasks for size, shape and distance perception. All participants were allowed to use additional time to practice more, if wanted.

Testing Phase

Testing Phase was divided into three sessions for size, shape and distance perception tests, respectively. Each session was designed with eight tasks. As Table 6.2 shows, the complexity of objects was getting higher as the number of components of an object increased.

Table 6.2: # of sphere components in the perception tasks.

Tasks	# of sphere components							
	#1	#2	#3	#4	#5	#6	#7	#8
Size and Shape	6	8	9	9	10	10	11	11
Distance	8	9	9	10	10	11	11	15

Per task, three objects were presented to a participant as shown in Figure 6.1. For each task, the participant was allowed to use up to 1.5 minutes, shorter than 3 minutes used in the second training session. The objects designed for this testing phase were more complicated, compared to the objects used in the second training session. All participants were required to take a break after each session. All participants were also informed that they were allowed to take a break after each task if they want. The performed tasks during the experiment are as follows,

- First session: size perception task

Per task, each participant was asked to first observe one of three objects (Figure 6.7) focusing on the size of components, not the overall scale of the object. The first observed object was given by the experimenter. Then the participant was required to find which one from the other two objects had the same components’ sizes as the first observed object. After the

participant selected an object within the given time or the allocated time was over, the screen was blocked to prevent the participant from continuously looking at the objects. After the participant answered the number (1, 2, or 3) of the selected object, the next task with three objects was presented to the participant.



Figure 6.7: An example of size-perception tasks.

- Second session: shape perception task

The procedure of the second session was exactly same as described above for the first session of size perception tasks (Figure 6.8). However, for the shape perception task, the participant observed an object indicated by the experimenter focusing on the shape, i.e., the angles of the object's components. The participant was required to find which one from the other two objects had the same shape as the first observed object. The remaining parts were also same as the first session. Three objects per task provided for this second session were very similar to the first session, but rotated at randomly different angles.

- Third session: distance perception task

The procedure of the second session was exactly same as described above for the first session of size perception tasks. However, for the distance perception task, each object includes two balls (sphere components) with yellowish green color (Figure 6.9). Each participant was asked to observe an object indicated by the experimenter, focusing on the distance between two balls. It was additionally explained that the distance between two balls meant the dis-

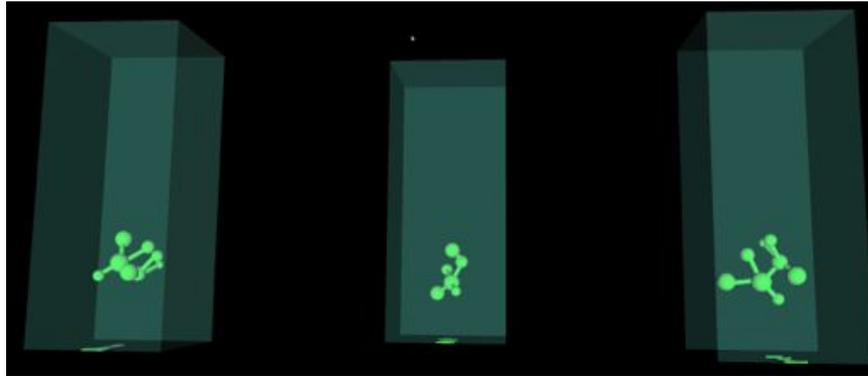


Figure 6.8: An example of shape-perception tasks.

tance between two centers of the two balls. All participants were informed to consider the size of balls when performing the distance perception tasks.

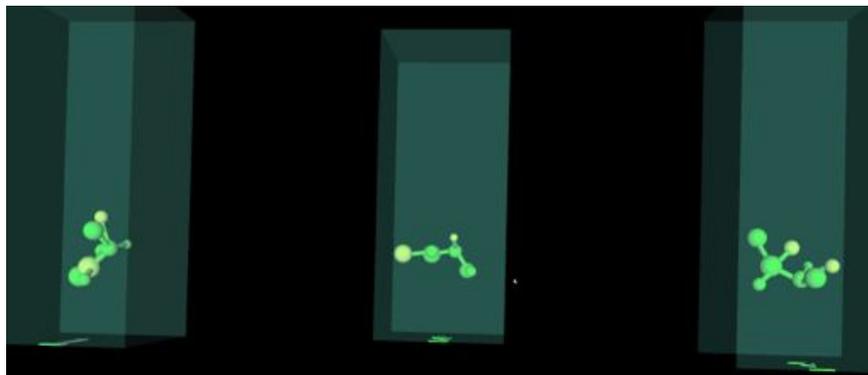


Figure 6.9: An example of distance-perception-tasks.

The multiple-choice tasks used for our size (Figure 6.11), shape (Figure 6.12) and distance (Figure 6.13) in our PerceptStudy are provided at the end of this chapter.

Measurements

We recorded the scores based on the correct answers provided by the participants for each session. Based on the scores of two NavTechs groups per session, we conducted one-way ANOVA to examine if there is any significant difference on the scores means in two NavTechs.

6.2.2 Results

It was confirmed that the collected data (i.e., *scores* of participants) per group follows a normal distribution by using the Ryan-Joiner test. Figure 6.10 shows the means of the scores from three types of perception tasks as summarized in Table 6.3. The data were analyzed using one-way ANOVA that had one between-participants factor (i.e., NavTechs). The result showed that the participants in the FWIP group performed the distance perception tasks significantly better than the participants in the JS group, $F(1, 38) = 10.537, p = .002 (< .05)$ while there were no significant differences on the performance of size and shape perception tasks in two NavTech groups.

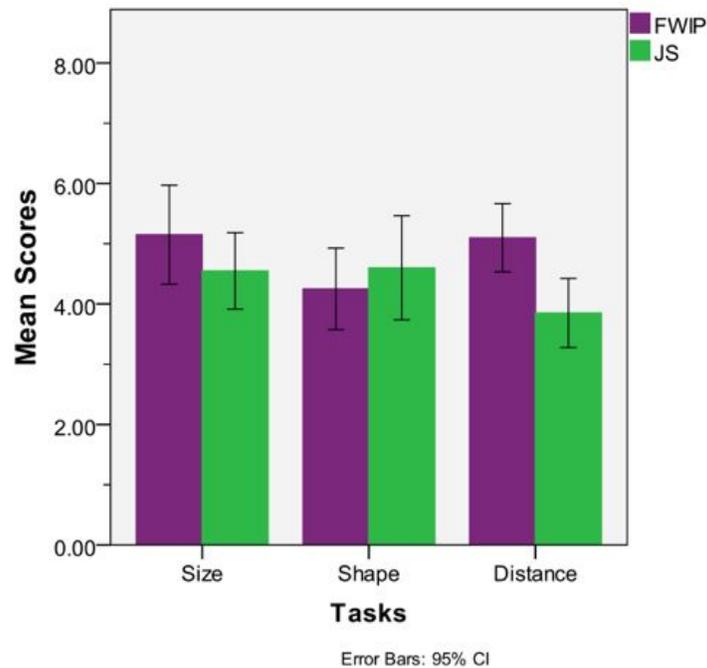


Figure 6.10: Scores means of two NavTech groups for the size, shape and perception tasks.

We also conducted another one-way ANOVA that had one within-participants factor (i.e., perception tasks). Although there were no significant differences on the performance in three pairwise comparisons, i.e., size vs. shape, shape vs. distance and size vs. distance, within each NavTech group, we found that there are some trends suggesting that size perception might be related to the ‘walking’ action because the scores means of the distance perception tasks in the FWIP group

Table 6.3: Scores means of two NavTech groups for the size, shape and perception tasks.

Tasks	FWIP	JS
Size	$M = 5.15, SD = 1.755$	$M = 4.55, SD = 1.36$
Shape	$M = 4.25, SD = 1.45$	$M = 4.6, SD = 1.85$
Distance	$M = 5.1, SD = 1.2$	$M = 3.85, SD = 1.23$

were similar to those of the size perception tasks as 5.1 and 5.15, respectively. Details are discussed in §6.2.3.

6.2.3 Discussion

Perceptual Ability Maintained by Transferred Action

PerceptStudy was designed to answer the question, *does perceptual ability dependent on a specific action is maintained by its transferred action?* Specifically our interest was whether the perceptual ability dependent on the ‘walking’ action is maintained by its transferred action (‘finger-walking’ action) as we provided our theoretical reasoning in §3.1.

Based on our literature review for PerceptStudy, we found that there is no research to support whether the ‘walking’ action is coupled with either size or shape perception while it has been shown that the ‘walking’ action is related to distance (or depth) perception. Then we provided our conjecture using common experiences with object perception in our everyday lives, and hypothesized that *there will be better performance in distance perception with the FWIP than with the JS, while there will be no difference in size and shape perception performance between the FWIP and the JS.*

The results of our PerceptStudy successfully support our hypothesis and also additionally support our design concept that humans can still maintain the abilities of (spatial) learning and perception by the transferred action when the abilities were dependent on the original action. Since no liter-

ature supports yet that the ‘walking’ action is not coupled with size and shape perception, further study is needed. However, our PerceptStudy shows that distance perception ability is significantly influenced by the ‘finger-walking’ action (transferred action), which was also supported by the ‘walking’ action (original action).

We did not include any walking-like NavTech for this study because our CAVE system has an open back wall that the users with a walking-like NavTech inevitably and continuously encounter, in order to observe the objects by moving around. Unlike maze-based studies, there was no way to prevent the participants from encountering the open back wall. It would be more interesting if a walking-like NavTech is involved in PerceptStudy using a fully-immersive VE system such as six walls based CAVE or HMD.

Relationship Between Size and Distance Perception

As shown in Figure 6.10, the scores of size and distance perception tasks in the FWIP group were almost same although there was no significant difference on size perception in the FWIP and the JS. This observation can be supported by the concept of *percept-percept coupling*, the best known coupling of which is that between perceived size and perceived egocentric distance, referred as size-distance invariance hypothesis [23]. Since it was not our intention to investigate the concept of percept-percept coupling, further discussion would be beyond the scope of this dissertation. However, it was still quite interesting that our study results showed this percept-percept coupling trend between size and distance perception with the FWIP. Further research on this percept-percept coupling would be suggested.

High Dropout Rate in JS_{table}

It turned out that the cyber-sickness induced by the JS_{table} was more severe than our expectation. We compared the proportions of the dropout rates between three NavTechs; FWIP: 0%, JS: 13% and JS_{table}: 38%, using a Chi-square test. The results showed that there is a significant difference

in proportions between three NavTech groups, $(\chi^2)(2, N=65) = 11.22, p = .004 (< .05)$. From this result, we strongly suggest that further study about the cyber-sickness should be performed. Especially, the FWIP and the JS_{table} were equally configured, so that the participants in two NavTech groups were not allowed to physically move except for the fingers (and the hands). However, the cyber-sickness was significantly different in two NavTechs, suggesting the transferred action may be able to diminish the symptoms (e.g., nausea and dizziness) of cyber-sickness.

Table 6.4 shows the dropout rates due to cyber-sickness in the maze-based studies described in the previous chapters and in our PerceptStudy described in this chapter. These comparisons suggest that spatial navigation tasks would cause more severe cyber-sickness than object-perception tasks. The dropout rate of the JS group in PerceptStudy was decreased, compared to the maze-based study. This result implies that the JS_{table} would have had higher dropout rate in the maze study than 38% (8 out of 21) shown in PerceptStudy if the JS_{table} was tested in the maze studies. Since the JS allowed the physical movement of participants but JS_{table} did not, we can assume that the physical movement would diminish the symptoms of cyber-sickness.

Table 6.4: Approximate dropout rates due to cyber-sickness in four different NavTechs.

Studies	FWIP	JS	JS _{table}	SF-WIP
Maze-based Study	8.3% (2 out of 24)	26% (7 out of 27)	N/A	4.8% (1 out of 21)
PerceptStudy	0% (0 out of 21)	9% (2 out of 22)	38% (8 out of 21)	N/A

Considering the dropout rates observed from our two different studies, further studies are needed to determine whether the transferred action (FWIP) without physical (whole-body) movement can effectively diminish the symptoms of cyber-sickness, such as nausea and dizziness, as much as the original action based NavTech (SF-WIP).

6.3 Chapter Summary

In this chapter, we explored whether there is a connection between distance perception and transferred action. As a action-transferred NavTech, we used the finger-walking-in-place (FWIP), compared with the non-walking common NaveTech (JS). The original action-based NavTech was referred to a walking-like NavTech, but not used in this study due to the used CAVE system's open back wall.

This exploration was attempted because our previous studies (Chapters 4 and 5) focusing on spatial knowledge acquisition did not directly suggest that our perceptual ability dependent on the original action is still maintained by the transferred action.

Since we hardly found any relevant literature investigating the effect of different NavTechs on perception, we devised our own study-design through several (informal) pilot studies. For our explorative study, named PerceptStudy in this chapter, we used the modified JS NavTech by using a wand-fixtured and a table where the wand input device of the JS was fixed (JS_{table}). Thus, we were able to provide the equal experiment condition to compare the task performance of the action-transferred NavTech (FWIP) and the non-walking NavTech (JS). However, due to the high dropout rate in the JS_{table} group, we stopped recruiting participants for the JS_{table} NavTech, and consequently we could not continue conducting the explorative study with the JS_{table} . Thus, the collected data from two NavTechs, FWIP and JS, were used for our data analysis.

We provided experiment tasks to explore three types of perception, i.e., size, shape and distance. For our PerceptStudy, we hypothesized that *there will be better performance in distance perception with the FWIP than with the JS, while there will be no difference on size and shape perception performance in the FWIP and the JS NavTechs.*

For the objective evaluation, we used eight multiple-choice tasks for each type of perception. The scores means of each type of perception task were compared in two NavTechs. Our study results showed that the participants in the FWIP group performed the distance perception tasks significantly better than the participants in the JS group while there were no significant differences on

the performance of size and shape perception tasks in two NavTech groups. Thus, our explorative study supports our hypothesis.

In addition to finding our main result, we observed an interesting trend that the scores means of size and distance perception tasks in the FWIP group were almost same, which can be explained by the concept of “percept-percept coupling” (size-distance invariance). Since further discussion is beyond the scope of this dissertation, further research is preferred on this percept-percept coupling.

Unexpectedly, the JS_{table} group produced the higher dropout rate, compared to the other NavTechs including our previous maze-based studies as well as PerceptStudy. Since the main factor(s) to cause this intolerable cyber-sickness is unknown yet, further research will be needed to resolve this issue. However, our observation indicates that transferred action may be able to address this issue of cyber-sickness.

Thus, our study results suggest that our perceptual ability dependent on the original action would be still maintained by the transferred action, regarding distance perception. Based on our observation from this explorative study, we suggested several further studies, in terms of the effect on percept-percept coupling of NavTechs and cyber-sickness caused by different NavTechs.

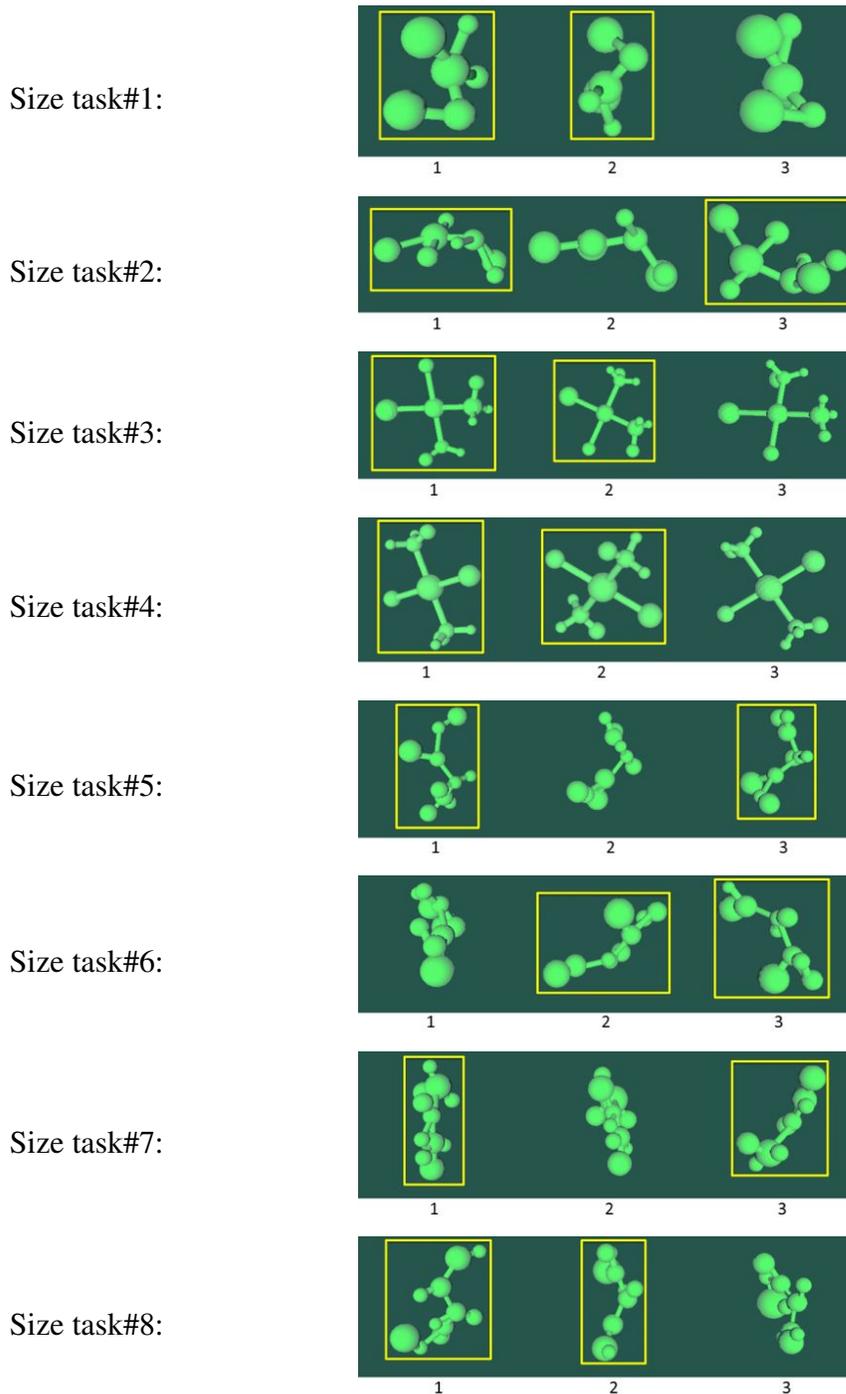


Figure 6.11: Size perception tasks (§6.2.1): two objects with the same size are marked with yellow rectangle.

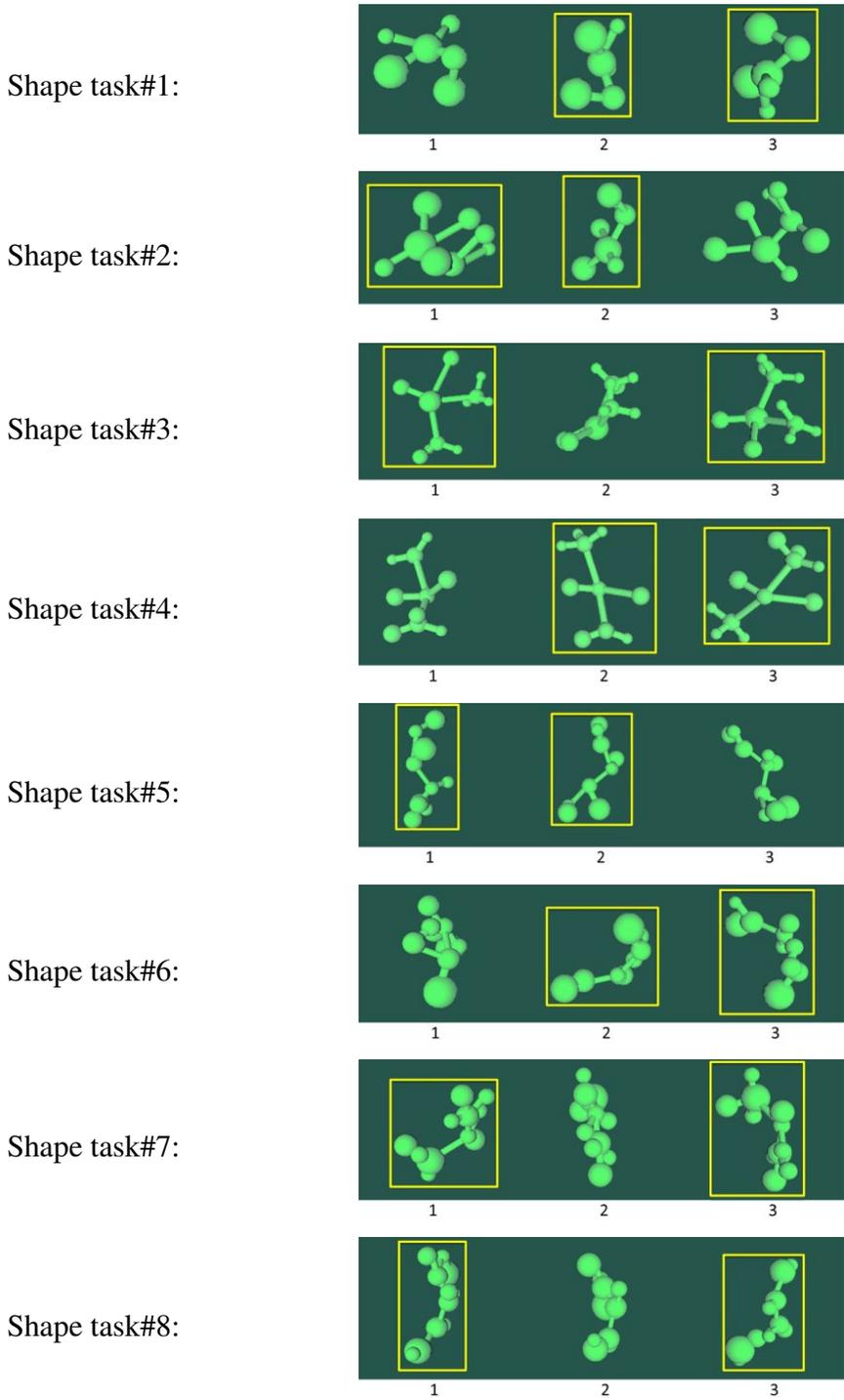


Figure 6.12: Shape perception tasks (§6.2.1): two objects with the same shape are marked with yellow rectangle.

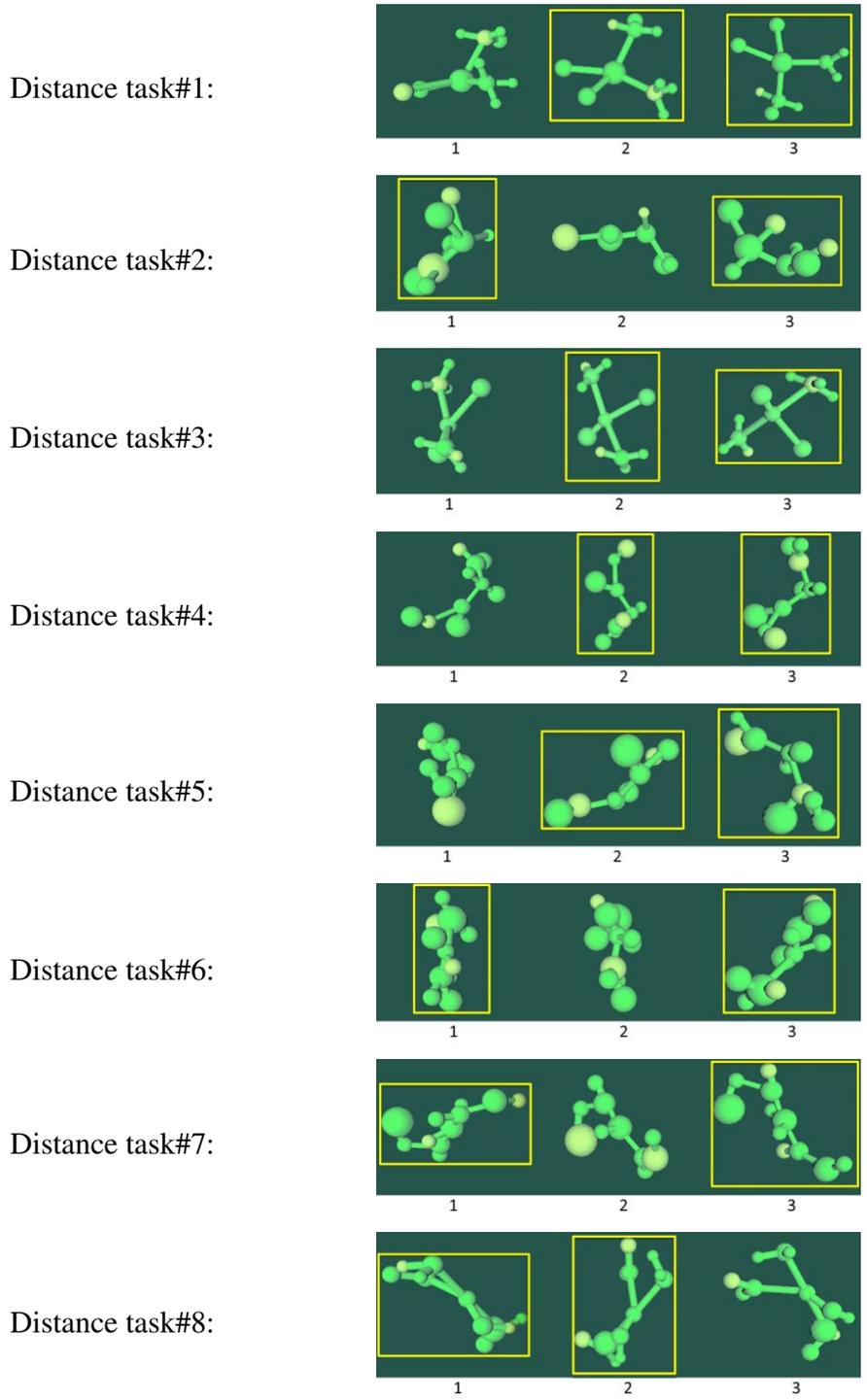


Figure 6.13: Distance perception tasks (§6.2.1): two objects with the same distance of two yellowish green components are marked with yellow rectangle.

Chapter 7

Conclusion

The purpose of this dissertation was to provide a new approach to design of convenient and effective navigation techniques (NavTechs) for spatial learning reducing whole-body fatigue, controlled space size, and/or system complexity in 3-D virtual environments (VEs). We proposed an action-inspired design approach of NavTechs for the purpose. We presented two types of action-inspired design approach, body-turn based and action-transferred approaches, implemented the NavTechs for the two types of action-inspired design approach, and demonstrated the effects of body-turn based and action-transferred NavTechs on spatial knowledge acquisition through empirical studies. In addition, we presented a new walking-in-place technique, named sensor-fusion walking-in-place (SF-WIP) to be compared with body-turn and action-transferred NavTechs in our empirical studies. Additionally, we presented an explorative study suggesting that our perceptual ability dependent on the original action would be still maintained by the transferred action, regarding distance perception.

Our formal studies described in this dissertation were approved by the Institutional Review Board at Virginia Tech.

7.1 Summary

The dissertation research was performed starting with examination of the previously developed NavTechs for effective spatial knowledge acquisition, and then incorporating our insights from the learning, action, perception, neuropsychological, neurophysiological theories to propose a new design approach that can address the design-trade offs related to designing effective and convenient NavTechs for spatial knowledge acquisition.

In Chapter 2, we reviewed the literature related to spatial knowledge and the relationship between spatial knowledge acquisition and navigation. This review was useful to understand the different types of spatial knowledge and why navigation is necessary to acquire effective spatial knowledge. We also understood that we need different assessment methods to evaluate the accuracy of different types of spatial knowledge acquired during navigation.

Previously proposed NavTechs were also reviewed through literature survey, dividing into walking-like and non-walking-like NavTechs. We understood that the traditional approach to improve/refine walking-like NavTechs cannot resolve the potential issues, such as body-fatigue, large-controlled space and complex system configuration, while maintaining the effectiveness in spatial knowledge acquisition. Hence, non-walking-like and non-body-control based NavTechs are still more popular and commonly used although resulting in less effective spatial knowledge acquisition. From this observation, we found design trade-offs between the walking-like and the non-walking common NavTechs, i.e., the walking-like NavTechs support effective spatial knowledge acquisition, but less convenient use; the non-walking common NavTechs are usually simple and convenient to use but less effective in spatial knowledge acquisition. The design trade-offs led us to our research motivation, i.e., expected NavTechs should be able to reduce whole-body fatigue, controlled space size, and/or complexity of system configuration, yet maintain the effective spatial benefits including spatial knowledge acquisition.

The previously performed comparative studies were reviewed focusing on walking-like versus non-walking and non-body-control based NavTechs. From the review, we found that there was no study

to show the consistent effectiveness of a NavTech in both route and survey knowledge acquisition tasks, and even there was very little research to attempt to measure different types of spatial knowledge. Since different types of spatial knowledge, e.g., route and survey knowledge, are acquired from the different experiences, different assessment methods and different tasks should be used, such as route replication for assessing route knowledge and sketching a map for assessing survey knowledge. The expected NavTechs with a new design approach can support both route and survey knowledge acquisition effectively.

In Chapter 3, we provided our reasoning from the theories in learning and perception-action, and the motor equivalence theory. We found that *perception* and *action* plays a central role for spatial learning. We focused more on *action* rather than *perception* to propose our new design approach. We proposed two types of action-inspired design approaches, *body-turn based* and *action-transferred* approaches.

Although *body-turn based* design approach was used by few other studies before, no study has attempted to investigate the effect of *body-turn* on route and survey knowledge acquisition separately. Hence, we presented the design and implementation of our body-turn based NavTech, and demonstrated its effect on route and survey knowledge acquisition.

An action-transferred approach is newly proposed grounded in the motor equivalence theory in this dissertation. Although the motor equivalence theory (specifically, “action-transfer”) has been proved in various research areas [27, 41] including neuroscience and neurophysiology using fMRI [81, 98], applications and implications of the theory have not been investigated in designing interaction techniques including NavTechs. We believe that we are the first contributors to recognizing the value of the theory and to adopting the theory to design effective NavTechs.

In Chapter 4, we presented the body-turn based NavTech (JS_m) designed with the action-inspired approach (§3.2), and described our evaluation of the JS_m through a comparative study in a large-scale, large-extent and visually impoverished virtual space (i.e., maze) using a CAVE virtual environment system. Two different types of NavTechs, a common non-body-based NavTech (JS) and a walking-like NavTech, were compared with JS_m . In particular, we newly developed a sensor-fusion

walking-in-place (SF-WIP) to provide a walking-like NavTech not only because the existing WIP NavTechs were hardly adopted to our CAVE system but also because some potential issues, e.g., latencies, tethered interface and no support of dynamic walking-speed change, of existing WIP NavTechs were not fully addressed yet. After our validity test of the SF-WIP, we employed the SF-WIP for our comparative study. Thus, our comparative study focused on two comparisons, JS_m vs. JS and JS_m vs. SF-WIP.

In the comparative study in Chapter 4, our evaluation was focused on measuring the accuracy of route and survey knowledge acquired through the route replication task and extensive exploration of the maze. We provided our own evaluation methods because the known evaluation methods such as shortest traveled distance, shortest task-completion-time or counting wrong turns, were not applicable to our evaluation. Route knowledge acquired by a participant was assessed using *penalty scores* given to the wrong and missing segment(s) that were not in the reference route while survey knowledge acquisition of a participant was examined using a map-based multiple-choice.

Based on our analysis on route knowledge acquisition of all participants, we found that only the SF-WIP supported the participants to acquire more accurate route knowledge than the other NavTech groups, i.e., JS and JS_m. Regarding survey knowledge acquisition, our study results statistically showed that the participants of JS_m and SF-WIP groups acquired survey knowledge while the participants of the JS group did not acquire survey knowledge.

Thus, our comparative study described in Chapter 4 supports that one of our action-inspired approaches, i.e., body-turn based approach, can be used to design effective NavTechs for survey knowledge acquisition, by demonstrating that the body-turn based NavTech (JS_m) can effectively support survey knowledge acquisition. Observing our study results described in Chapter 4 and previously performed study results [77], it appears that body-turn may be a dominant factor to influence the effect on survey knowledge acquisition in visually-impooverished virtual space.

Our study in Chapter 4 also suggests that walking-like and body-turn-based NavTechs could be selectively used. This suggestion can be guidance on the choice of action for some applications to minimize the effort to design/develop effective NavTechs for spatial knowledge acquisition.

Implementing walking-like NavTechs would need more time, more complex hardware, more complex algorithms and lots of usability studies for fine-tuning, compared to body-turn or non-walking common NavTechs. If learning spatial layout of the environment (i.e., survey knowledge) is more important to some applications, a body-turn based NavTech would be enough. However, if there are the cases that the full effects of route and survey knowledge are needed, walking-like NavTechs would be more likely suggested as many relevant studies suggest. Further investigation would be beneficial to support our guidance to provide more detailed guidelines.

In addition, since our test VE is based on a large-scale, large-extent and visually impoverished space, the results of our study support that people can be trained in such environments to effectively acquire spatial knowledge for some applications, such as military training in large abandoned buildings or deserted areas, firefighter training in burn buildings with no signs, covered by fire and smoke, and large-scale disaster rescue training in earthquake or mine.

In Chapter 5, we presented how we can develop an action-transferred navigation technique (NavTech) by using “finger-walking” as common intuition. In order to properly provide feasible FWIP technique for navigation in VEs, we went through several iterations of design and implementation to refine our FWIP. Then, we performed a comparative user study that successfully demonstrated the effect of the FWIP on both route and survey knowledge acquisition (i.e., spatial learning), compared to the wand-and-joystick based NavTech (JS), while showing the similar spatial learning effect to that of the sensor-fusion walking-in-place (SF-WIP) NavTech.

Thus, in Chapter 5 we provided a possible answer to our key research question: *how can we design a convenient NavTech providing effective spatial benefits with reduced whole-body fatigue, controlled space size, and/or system-configuration complexity?*, by presenting the details of design and implementation of the FWIP, which is the NavTech based on lightweight action (using small-muscle groups) transferred from the original ‘walking’ action, and by demonstrating the effectiveness of the FWIP for spatial learning in our empirical study. Although our conclusion is drawn from the empirical study using one transferred action based NaveTech, i.e., FWIP, and is therefore not direct evidence at the neural level, it should be notable that our action-transferred

design approach for effective spatial learning is strongly supported by the theories that have been demonstrated by a number of studies. In addition, we discussed that cyber-sickness can be diminished by transferred action without physical movement.

Then we suggested a guidance how our new design approach using the action-transfer concept can be applied to developing other new interaction techniques, show a possible systematic procedure to develop action-transferred interaction techniques when the effectiveness of original actions is known. In order to provide the usefulness of this systematic procedure to design new action-transferred interaction techniques, there should be further investigation followed.

In Chapter 6, we explored whether there is a connection between distance perception and transferred action. As a action-transferred NavTech, we used the finger-walking-in-place (FWIP), compared with the non-walking common NaveTech (JS). The original action-based NavTech was referred to a walking-like NavTech, but not used in this study due to the used CAVE system's open back wall. This exploration was attempted because our previous studies (Chapters 4 and 5) focusing on spatial knowledge acquisition did not directly suggest that our perceptual ability dependent on the original action is still maintained by the transferred action.

We provided newly designed experiment tasks to explore three types of perception, i.e., size, shape and distance. For our PerceptStudy, we hypothesized that *there will be better performance in distance perception with the FWIP than with the JS, while there will be no difference on size and shape perception performance in the FWIP and the JS NavTechs*. Our study results showed that the participants in the FWIP group performed the distance perception tasks significantly better than the participants in the JS group while there were no significant differences on the performance of size and shape perception tasks in two NavTech groups. Thus, our explorative study supports our hypothesis.

In addition to finding our main result in Chapter 6, we observed an interesting trend that the mean scores of size and distance perception tasks in the FWIP group were almost same, which can be actually explained by the concept of “percept-percept coupling” (size-distance invariance). Since further discussion is beyond the scope of this dissertation, further research is preferred on this

percept-percept coupling. Unexpectedly, the JS_{table} group produced the higher dropout rate, compared to the other NavTechs including our previous maze-based studies as well as PerceptStudy. Since the main factor(s) to cause this intolerable cyber-sickness is unknown yet, further research will be needed to resolve this issue.

7.2 Contributions

This dissertation provided a new approach to design of convenient and effective NavTechs providing spatial benefits with reduced whole-body fatigue, controlled space size, and/or system complexity in 3-D virtual environments (VEs) and demonstrated the effect of our new design approach through several empirical studies. The specific original contributions are described in this section.

The main contribution of this research is that we propose an *action-inspired approach* to designing convenient and effective NavTechs for spatial knowledge acquisition/spatial learning. The action-inspired approach is based on our theoretical reasoning and review on empirical studies. We identified two types of action-inspired approach, body-turn based and action-transferred. Body-turn based approach replaces translational control of walking-like navigation techniques with more convenient control for navigation to resolve the issues presented from walking-like navigation techniques. Action-transferred approach addresses the design trade-offs between effectiveness and convenience, the core concept of which is grounded in the motor equivalence theory.

In particular, the action-transferred approach leverages the motor equivalence theory as a core concept. We recognized the value of the motor equivalence theory, adopted the theory to design navigation (interaction) techniques, and demonstrated the effectiveness of the design approach using the empirical studies in Virtual Reality (VR) and Human-Computer Interaction (HCI) areas. Although the motor equivalence theory (specifically, “action-transfer”) has been supported in various research areas [27, 41] including neuroscience and neurophysiology using fMRI [81, 98], applications and implications of the theory have not been investigated in VR and HCI areas.

In addition, we demonstrated that spatial learning abilities, such as route and survey knowledge

acquisition, can be transferred when bipedal walking (original action) is replaced with finger-based walking-action (transferred action). This has broader implications for designing interaction techniques where it is desirable to replace the biological effector(s) with the other(s). For example, the action transfer would be needed when the user has a disability that compromises the use of a body part, or when a replacement is desired for fatigue or convenience reasons (as argued for finger-walking-in-place).

Related to our theoretical reasoning, we presented another user study designed to explore if the transferred action is still coupled with the perceptual ability that is known as coupled with the original action. Three types of perception, i.e., size, shape and distance were explored. We hypothesized that our perceptual ability, e.g., distance perception, dependent on a specific action, e.g., walking, is still maintained by its transferred action, e.g., finger-walking. Our study results showed that the participants in the FWIP group performed the distance perception tasks significantly better than the participants in the JS group while there were no significant differences on the performance of size and shape perception tasks in two NavTech groups. Thus, this dissertation successfully demonstrated our theoretical reasoning and our design approaches to convenient and effective navigation techniques for spatial learning through our empirical studies.

The second contribution of this research is the development of new NavTechs, i.e., finger-walking-in-place (FWIP) and sensor-fusion-walking-in-place (SF-WIP). We presented how to design and implement FWIP and SF-WIP in detail. In addition, we showed the implementation of FWIP and SF-WIP using commodity smartphones and tablet-devices, so that FWIP and SF-WIP can be easily replicated by other researchers and can be applicable for many spatial tasks. Since we also demonstrated the effectiveness of FWIP and SF-WIP particularly in spatial knowledge acquisition, many VE training or educational applications can adopt FWIP or SF-WIP for training people for the purpose of learning spatial layout or routes.

7.3 Future Work

Although the body-turn based NavTech can resolve some issues of walking-like NavTechs, it was only effective on survey knowledge acquisition, while the action-transferred NavTech was effective on both route and survey knowledge acquisition as well as resolving the issues of walking-like NavTechs in our study. Hence, future work is suggested more focusing on this action-transferred design approach.

Our action-transferred NavTech, FWIP, would allow to extend possible applications where effective spatial learning is essential but physical training is not necessary, while effective spatial learning is still useful for mission-critical training applications in VEs. In order to adopt the FWIP for other spatial learning applications, more empirical studies are preferred using different types of virtual space, such as large-scale with rich visual information. In addition, more examples of action-transferred NavTechs, such as arm-walking-in-place or elbow-walking-in-place, would be suggested to support our action-transferred design approach more robust.

Although our explorative study suggests that our distance perception is still tightly connected with the transferred action, it would be suggested to intensively investigate the connection between the transferred action (e.g., FWIP) and different types of perception, which would be corresponding to the connection between the original action (e.g., walking) and the certain types of perception.

Based on our observation from our empirical studies, especially in Chapter 6, further study on cyber-sickness is strongly suggested. In particular, considering the relative low dropout rate of the FWIP, further research would be needed to determine whether the transferred action, i.e., the FWIP, can effectively diminish the symptoms of cyber-sickness, such as nausea and dizziness, without physical (whole-body) movement, as much as the original action based walking-like NavTech.

Our action-transferred design approach is based on a broader concept grounded in the motor equivalence theory suggesting that we can replace one biological effector (i.e., body part) with another and retain the associated natural and learned capabilities. This can have broader implications for designing interaction techniques, not limited to navigation techniques, where it is desirable to re-

place the biological effector(s) with the other(s). For example, the action transfer would be needed when the user has a disability that compromises the use of a body part, or when a replacement is desired for fatigue or convenience reasons (as argued for our study in this article). In order to use this action-transferred design concept to design other types of interaction techniques, it would be suggested to provide a systematic procedure for developing interaction techniques from the original actions when the certain effects of the original actions should be known. Based on the systematic approach, we hope that this action-transferred design concept can be more extensively used by other researchers.

We believe that our action-transferred design approach can open further research opportunities and applications in human computer interaction (HCI) research area, for example, by incorporating an embodied perspective into our action-transferred design approach although our design approach was more focused on supporting (spatial) learning effect. Since embodiment has been already adopted for designing user interfaces and for enhancing users' interactive experience of computation in HCI, it would be an interesting research topic to investigate how we can design user interfaces / interaction techniques to improve learning effect from the embodied perspective when involving transferred action.

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Appendix A

Experiment Documents for Evaluation of Action-Based Design Approach

A.1 Approval Letter from IRB at Virginia Tech

A.1.1 The first approval letter (May 2011 to May 2012)



VirginiaTech

Office of Research Compliance
 Institutional Review Board
 2000 Kraft Drive, Suite 2000 (0497)
 Blacksburg, Virginia 24060
 540/231-4606 Fax 540/231-0959
 e-mail irb@vt.edu
 Website: www.irb.vt.edu

MEMORANDUM

DATE: May 9, 2011

TO: Denis Gracanin, Ji-Sun Kim

FROM: Virginia Tech Institutional Review Board (FWA00000572, expires October 26, 2013)

PROTOCOL TITLE: Finger-Driven Interaction Technique for Wayfinding in Virtual Environments

IRB NUMBER: 07-298

Effective May 31, 2011, the Virginia Tech IRB Chair, Dr. David M. Moore, approved the continuation request for the above-mentioned research protocol.

This approval provides permission to begin the human subject activities outlined in the IRB-approved protocol and supporting documents.

Plans to deviate from the approved protocol and/or supporting documents must be submitted to the IRB as an amendment request and approved by the IRB prior to the implementation of any changes, regardless of how minor, except where necessary to eliminate apparent immediate hazards to the subjects. Report promptly to the IRB any injuries or other unanticipated or adverse events involving risks or harms to human research subjects or others.

All investigators (listed above) are required to comply with the researcher requirements outlined at <http://www.irb.vt.edu/pages/responsibilities.htm> (please review before the commencement of your research).

PROTOCOL INFORMATION:

Approved as: **Expedited, under 45 CFR 46.110 category(ies) 6, 7**

Protocol Approval Date: **5/31/2011** (protocol's initial approval date: **5/31/2007**)

Protocol Expiration Date: **5/30/2012**

Continuing Review Due Date*: **5/16/2012**

*Date a Continuing Review application is due to the IRB office if human subject activities covered under this protocol, including data analysis, are to continue beyond the Protocol Expiration Date.

FEDERALLY FUNDED RESEARCH REQUIREMENTS:

Per federal regulations, 45 CFR 46.103(f), the IRB is required to compare all federally funded grant proposals / work statements to the IRB protocol(s) which cover the human research activities included in the proposal / work statement before funds are released. Note that this requirement does not apply to Exempt and Interim IRB protocols, or grants for which VT is not the primary awardee.

The table on the following page indicates whether grant proposals are related to this IRB protocol, and which of the listed proposals, if any, have been compared to this IRB protocol, if required.

Invent the Future

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY

An equal opportunity, affirmative action institution

Date*	OSP Number	Sponsor	Grant Comparison Conducted?

*Date this proposal number was compared, assessed as not requiring comparison, or comparison information was revised.

If this IRB protocol is to cover any other grant proposals, please contact the IRB office (irbadmin@vt.edu) immediately.

cc: File

A.1.2 The second approval letter (May 2012 to May 2013)



VirginiaTech

Office of Research Compliance
 Institutional Review Board
 2000 Kraft Drive, Suite 2000 (0497)
 Blacksburg, Virginia 24060
 540/231-4606 Fax 540/231-0959
 e-mail irb@vt.edu
 Website: www.irb.vt.edu

MEMORANDUM

DATE: May 1, 2012

TO: Denis Gracanic, Ji-Sun Kim

FROM: Virginia Tech Institutional Review Board (FWA00000572, expires May 31, 2014)

PROTOCOL TITLE: Finger-Driven Interaction Technique for Wayfinding in Virtual Environments

IRB NUMBER: 07-298

Effective May 31, 2012, the Virginia Tech IRB Chair, Dr. David M. Moore, approved the continuation request for the above-mentioned research protocol.

This approval provides permission to begin the human subject activities outlined in the IRB-approved protocol and supporting documents.

Plans to deviate from the approved protocol and/or supporting documents must be submitted to the IRB as an amendment request and approved by the IRB prior to the implementation of any changes, regardless of how minor, except where necessary to eliminate apparent immediate hazards to the subjects. Report promptly to the IRB any injuries or other unanticipated or adverse events involving risks or harms to human research subjects or others.

All investigators (listed above) are required to comply with the researcher requirements outlined at <http://www.irb.vt.edu/pages/responsibilities.htm> (please review before the commencement of your research).

PROTOCOL INFORMATION:

Approved as: **Expedited, under 45 CFR 46.110 category(ies) 6, 7**

Protocol Approval Date: **5/31/2012 (protocol's initial approval date: 5/31/2007)**

Protocol Expiration Date: **5/30/2013**

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FEDERALLY FUNDED RESEARCH REQUIREMENTS:

Per federal regulations, 45 CFR 46.103(f), the IRB is required to compare all federally funded grant proposals / work statements to the IRB protocol(s) which cover the human research activities included in the proposal / work statement before funds are released. Note that this requirement does not apply to Exempt and Interim IRB protocols, or grants for which VT is not the primary awardee.

The table on the following page indicates whether grant proposals are related to this IRB protocol, and which of the listed proposals, if any, have been compared to this IRB protocol, if required.

Invent the Future

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY

An equal opportunity, affirmative action institution

Date*	OSP Number	Sponsor	Grant Comparison Conducted?

*Date this proposal number was compared, assessed as not requiring comparison, or comparison information was revised.

If this IRB protocol is to cover any other grant proposals, please contact the IRB office (irbadmin@vt.edu) immediately.

cc: File

A.2 Approved Informed Consent from IRB at Virginia Tech

A.2.1 The first “Informed Consent” (May 2011 to May 2012)

Informed Consent for Participant of Investigative Project
Virginia Polytechnic Institute and State University

Title of Project: **Comparison of Navigation Techniques in 3D Immersive Virtual Environments**

Principal Investigator: Dr. Denis Gracanin

I. THE PURPOSE OF THIS RESEARCH/PROJECT

You are invited to participate in a study of interaction in a 3D immersive virtual environment (i.e., CAVE). This research studies the ways people act and work in a 3D virtual world. This study involves experimentation for the purpose of evaluating and improving the user interface and observing user behaviors in virtual environments.

II. PROCEDURES

You will be asked to fill out pre-experiment questionnaire with regard to your background and spatial ability.

You will be asked to perform a set of tasks using a virtual environment system, including practice tasks. These tasks consist of navigating through 3D virtual mazes by following waypoints and by free exploration without waypoints. You will use one interface to perform a set of tasks in the CAVE™ system. We are **not evaluating you or your performance in any way**; you are helping us to evaluate our system. The time you take to do each task and other aspects of your interaction with the system will be measured. You may be asked questions during and after the evaluation, in order to clarify our understanding of your evaluation.

You will also be asked to fill out post-experiment questionnaire after you finish the experiment tasks.

The session will last less than 90 minutes in total including short breaks. The tasks are not tiring but need your attention. You are welcome to take a break as needed. You may also terminate your participation at any time for any reason.

You will be given full instructions before every task. Because we are measuring a range of abilities, some tasks will be easy and others difficult. It is important that you understand the instructions before beginning each task. If anything is unclear, be sure to ask us questions.

III. RISKS

The proposed experiments are straightforward tests using our hands/fingers/legs in virtual environments. Participation involves standing or walking in place on a semi-enclosed platform with three walls on the floor and performing experiment tasks. The physical components of these tasks are not stressful, and include walking in place or standing on the floor by allowing to turn the head. The only foreseeable physical risks are slight eye and leg strain, dizziness, or mild nausea. There are no known mental risks.

If you experience any eye or leg strain, dizziness, or nausea during the session, then please step away from the floor and take a break. The investigator will explain when you can take such breaks. If you are having trouble with any task, please tell us. If dizziness or nausea becomes uncomfortable, you will be allowed to leave with no penalty.

IV. BENEFITS OF THIS PROJECT

Your participation in this study will provide information that may be used to improve the interface design of virtual environments hardware and/or software. No guarantee of benefits has been made to encourage you to participate. You may receive a synopsis summarizing this research when completed if you want. You are requested to refrain from discussing the evaluation with other people who might be in the candidate pool from which other participants might be drawn.

V. EXTENT OF ANONYMITY AND CONFIDENTIALITY

The results of this study will be kept strictly confidential. Your written consent is required for the researchers to release any data identified with you as an individual to anyone other than personnel working on the project. The information you provide will have your name removed and only a subject number will identify you during analyses and any written reports of the research.

The experiment may be taken by a camera. We are interested in observing participants' behaviors. We avoid taking a video of participants' faces. If it is taken, the films (or files from a digital camera) will be stored securely, viewed only by the experimenters (Denis Gracanin and Ji-Sun Kim) and erased after those are stored in a secured hard drive. If the experimenters wish to use a portion of your picture for any other purpose, they will get your written permission before using it. Your signature on this form does not give them permission to show your picture to anyone else.

VI. COMPENSATION

1. For the participants from SONA system;
If you quit during the experiment for any reason within one hour, you will get 1 credit. Otherwise you will get 2 credits (full-credit).
2. For the participants from mailing lists;
Your participation is voluntary and unpaid.

VII. FREEDOM TO WITHDRAW

You are free to withdraw from this study at any time for any reason.

VIII. SUBJECT'S RESPONSIBILITIES AND PERMISSION

I voluntarily agree to participate in this study, and I know of no reason I cannot participate. I have read and understand the informed consent and conditions of this project. I have had all my questions answered. I hereby acknowledge the above and give my voluntary consent for participation in this project. If I participate, I may withdraw at any time without penalty. I agree to abide by the rules of this project

Signature

Date

Name (please print)

Contact: phone or address or

email address (OPTIONAL)

Should I have any questions about this research or its conduct, I may contact:

Investigator: Dr. Denis Gracanin Phone (540)231-2060
Associate Professor of Computer Science
Email: gracanin@vt.edu
Ji-Sun Kim (hideaway@vt.edu),

cc: the participant, Dr. Denis Gracanin

A.2.2 The second “Informed Consent” (May 2012 to May 2013)

Informed Consent for Participant of Investigative Project

Virginia Polytechnic Institute and State University

Title of Project: **Comparison of Navigation Techniques in 3D Immersive Virtual Environments**

Principal Investigator: Dr. Denis Gracanin

I. THE PURPOSE OF THIS RESEARCH/PROJECT

You are invited to participate in a study of interaction in a 3D immersive virtual environment (i.e., CAVE). This research studies the ways people act and work in a 3D virtual world. This study involves experimentation for the purpose of evaluating and improving the user interface and observing user behaviors in virtual environments.

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You will be asked to perform a set of tasks using a virtual environment system, including practice tasks. These tasks consist of navigating through 3D virtual mazes by following waypoints and by free exploration without waypoints. You will use one interface to perform a set of tasks in the CAVE™ system. We are **not evaluating you or your performance in any way**; you are helping us to evaluate our system. The time you take to do each task and other aspects of your interaction with the system will be measured. You may be asked questions during and after the evaluation, in order to clarify our understanding of your evaluation.

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You will be given full instructions before every task. Because we are measuring a range of abilities, some tasks will be easy and others difficult. It is important that you understand the instructions before beginning each task. If anything is unclear, be sure to ask us questions.

III. RISKS

The proposed experiments are straightforward tests using our hands/fingers/legs in virtual environments. Participation involves standing or walking in place on a semi-enclosed platform with three walls on the floor and performing experiment tasks. The physical components of these tasks are not stressful, and include walking in place or standing on the floor by allowing to turn the head. The only foreseeable physical risks are slight eye and leg strain, dizziness, or mild nausea. There are no known mental risks.

If you experience any eye or leg strain, dizziness, or nausea during the session, then please step away from the floor and take a break. The investigator will explain when you can take such breaks. If you are having trouble with any task, please tell us. If dizziness or nausea becomes uncomfortable, you will be allowed to leave with no penalty.

IV. BENEFITS OF THIS PROJECT

Your participation in this study will provide information that may be used to improve the interface design of virtual environments hardware and/or software. No guarantee of benefits has been made to encourage you to participate. You may receive a synopsis summarizing this research when completed if you want. You are requested to refrain from discussing the evaluation with other people who might be in the candidate pool from which other participants might be drawn.

V. EXTENT OF ANONYMITY AND CONFIDENTIALITY

The results of this study will be kept strictly confidential. Your written consent is required for the researchers to release any data identified with you as an individual to anyone other than personnel working on the project. The information you provide will have your name removed and only a subject number will identify you during analyses and any written reports of the research.

The experiment may be taken by a camera. We are interested in observing participants' behaviors. We avoid taking a video of participants' faces. If it is taken, the films (or files from a digital camera) will be stored securely, viewed only by the experimenters (Denis Gracanin and Ji-Sun Kim) and erased after those are stored in a secured hard drive. If the experimenters wish to use a portion of your picture for any other purpose, they will get your written permission before using it. Your signature on this form does not give them permission to show your picture to anyone else.

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If you quit during the experiment for any reason within one hour, you will get 1 credit. Otherwise you will get 2 credits (full-credit).
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Signature

Date

Name (please print)

Contact: phone or address or

email address (OPTIONAL)

Should I have any questions about this research or its conduct, I may contact:

Investigator: Dr. Denis Gracanin Phone (540)231-2060
Associate Professor of Computer Science
Email: gracanin@vt.edu
Ji-Sun Kim (hideaway@vt.edu),

cc: the participant, Dr. Denis Gracanin

A.3 Questionnaire: Pre-Experiment

A.3.1 Background

Subject# _____

Comparison of Navigation Techniques in 3D Immersive Virtual Environments

A. The following questions are about your general background.

- A1. Age: _____
- A2. Please circle your gender: Female Male
- A3. Occupation (if student, indicate graduate or undergraduate): _____
 Major / Area of specialization (if student): _____
- A4. Do you wear prescription glasses or corrective contact lenses? __ Yes / __No
 If yes, are you wearing them now? __ Yes / __No
 Do you have __ nearsightedness (myopia) or __ farsightedness
 (hypermetropia) ?
- A5. Please rate your experience level with Immersive Virtual Environments
 ___ Novice (No experience)
 ___ Some Experience (Less than or 4 times),
 please circle or write what you experienced: CAVE, HMD, Others _____
 ___ Intermediated (More than 4 times or programming experience)
 ___ Expert (Know very well Hardware/Software or developer)
- A6. Do you play video/computer games? __Yes / __No
 If yes, please estimate the number of hours per week you play these games: ___
 What type of games are they (e.g., strategy, fighting, or racing): _____
 Please list the names of game controllers that you have used. (e.g., Joystick)
 _____,
 Which controller is most comfortable for you? _____
- A7. Have you played any maze (do not include paper-based maze)? __Yes/ __No
 If yes, ___ only in virtual world/ ___ only in real world / ___ in both worlds
 If yes, do you enjoy playing the maze(s) in general? __Yes/ __No
- A8. Have you experienced looking for a target location in an unfamiliar
 environment by walking without any aid (e.g., GPS, instruction, or map)?
 ___ Yes / ___ No

A.3.2 Self-Report Sense of Direction

Subject# _____

Spatial Ability Test

This questionnaire consists of several statements about your spatial and navigational abilities, preferences, and experiences. After each statement, you should circle a number to indicate your level of agreement with the statement. Circle "1" if you strongly agree that the statement applies to you, "7" if you strongly disagree, or some number in between if your agreement is intermediate. Circle "4" if you neither agree nor disagree.

PLEASE MARK CAREFULLY BECAUSE SOME QUESTIONS ARE POSITIVE AND THE OTHERS ARE NEGATIVE.

- S1. I am very good at giving directions.
Strongly agree 1-----2-----3-----4-----5-----6-----7 *Strongly disagree*
- S2. I have a poor memory for where I left things.
Strongly agree 1-----2-----3-----4-----5-----6-----7 *Strongly disagree*
- S3. I am very good at judging distances.
Strongly agree 1-----2-----3-----4-----5-----6-----7 *Strongly disagree*
- S4. My "sense of direction" is very good.
Strongly agree 1-----2-----3-----4-----5-----6-----7 *Strongly disagree*
- S5. I tend to think of my environment in terms of cardinal directions (N, S, E, W).
Strongly agree 1-----2-----3-----4-----5-----6-----7 *Strongly disagree*
- S6. I very easily get lost in a new city.
Strongly agree 1-----2-----3-----4-----5-----6-----7 *Strongly disagree*
- S7. I enjoy reading maps.
Strongly agree 1-----2-----3-----4-----5-----6-----7 *Strongly disagree*
- S8. I have trouble understanding directions.
Strongly agree 1-----2-----3-----4-----5-----6-----7 *Strongly disagree*
- S9. I am very good at reading maps.
Strongly agree 1-----2-----3-----4-----5-----6-----7 *Strongly disagree*
- S10. I don't remember routes very well while riding as a passenger in a car.
Strongly agree 1-----2-----3-----4-----5-----6-----7 *Strongly disagree*
- S11. I don't enjoy giving directions.
Strongly agree 1-----2-----3-----4-----5-----6-----7 *Strongly disagree*
- S12. It's not important to me to know where I am.
Strongly agree 1-----2-----3-----4-----5-----6-----7 *Strongly disagree*

Subject# _____

S13. I usually let someone else do the navigational planning for long trips.

Strongly agree 1-----2-----3-----4-----5-----6-----7 *Strongly disagree*

S14. I can usually remember a new route after I have traveled it only once.

Strongly agree 1-----2-----3-----4-----5-----6-----7 *Strongly disagree*

S15. I don't have a very good "mental map" of my environment.

Strongly agree 1-----2-----3-----4-----5-----6-----7 *Strongly disagree*

STOP HERE AND CALL THE EXPERIMENT ADMINSTRATOR

A.3.3 Perspective Taking Spatial Orientation Test

Spatial Orientation Test

This is a test of your ability to imagine different perspectives or orientations in space. On each of the following pages you will see a picture of an array of objects and an “arrow circle” with a question about the direction between some of the objects. For the question on each page, you should imagine that you are standing at one object in the array (which will be named in the center of the circle) and facing another object, named at the top of the circle. Your task is to draw an arrow from the center object showing the direction to a third object from this facing orientation.

Look at the sample item on the next page. In this item you are asked to imagine that you are standing at the flower, which is named in the center of the circle, and facing the tree, which is named at the top of the circle. Your task is to draw an arrow pointing to the cat. In the sample item this arrow has been drawn for you. In the test items, your task is to draw this arrow. Can you see that if you were at the flower facing the tree, the cat would be in this direction? Please ask the experimenter now if you have any questions about what you are required to do.

There are 12 items in this test, one on each page. For each item, the array of objects is shown at the top of the page and the arrow circle is shown at the bottom. Please do not pick up or turn the test booklet, and do not make any marks on the maps. Try to mark the correct directions but do not spend too much time on any one question.

You will have 5 minutes for this test.

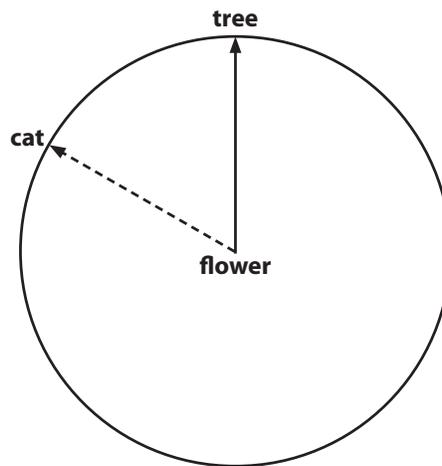
Spatial Orientation Test

Name: _____



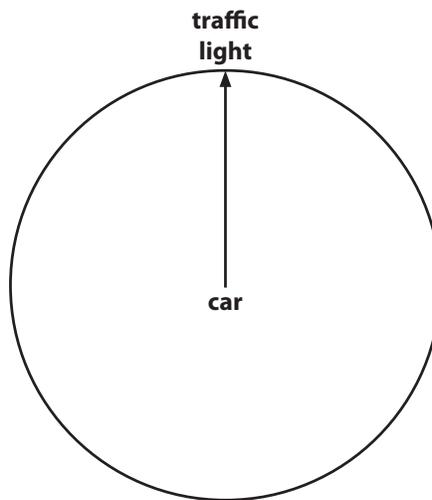
Example:

Imagine you are standing at the **flower** and facing the **tree**.
Point to the **cat**.



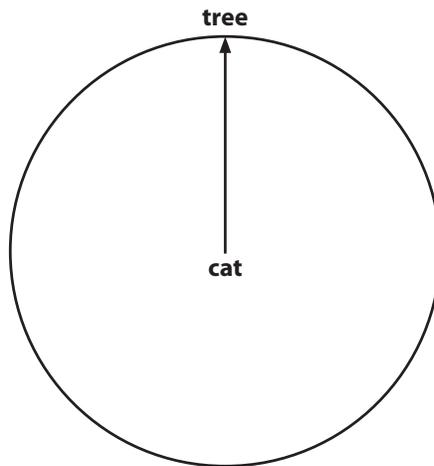


1. Imagine you are standing at the **car** and facing the **traffic light**.
Point to the **stop sign**.



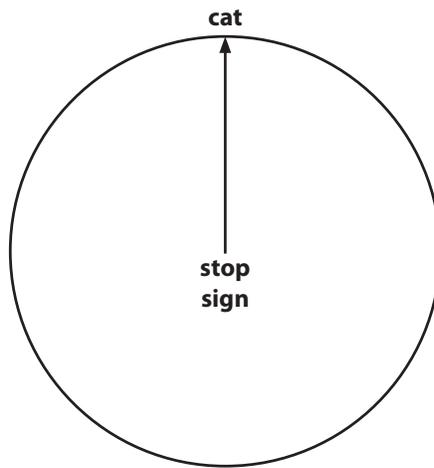


2. Imagine you are standing at the **cat** and facing the **tree**.
Point to the **car**.



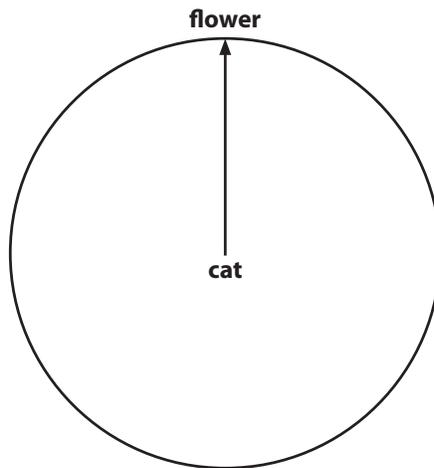


3. Imagine you are standing at the **stop sign** and facing the **cat**.
Point to the **house**.



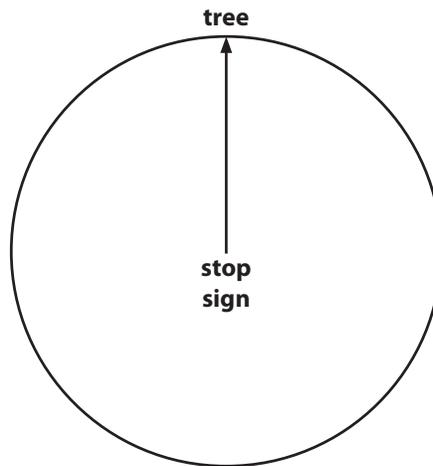


4. Imagine you are standing at the **cat** and facing the **flower**.
Point to the **car**.



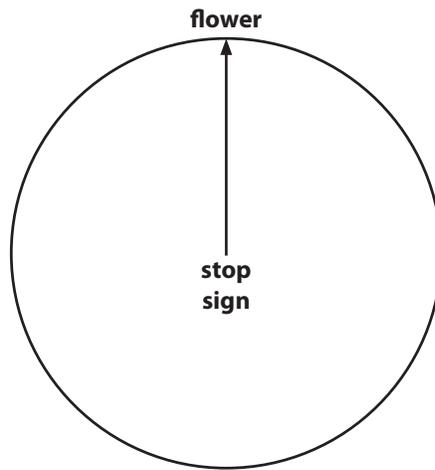


5. Imagine you are standing at the **stop sign** and facing the **tree**.
Point to the **traffic light**.



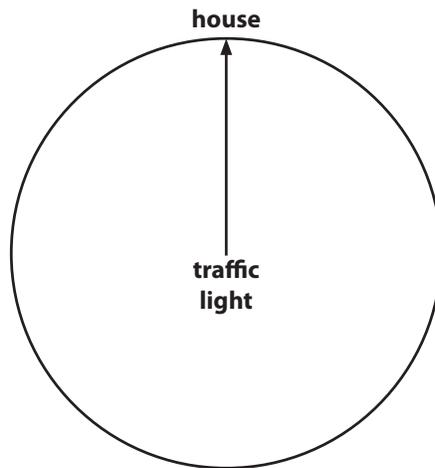


6. Imagine you are standing at the **stop sign** and facing the **flower**.
Point to the **car**.



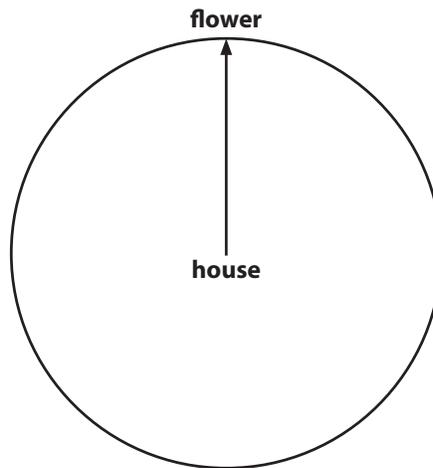


7. Imagine you are standing at the **traffic light** and facing the **house**.
Point to the **flower**.



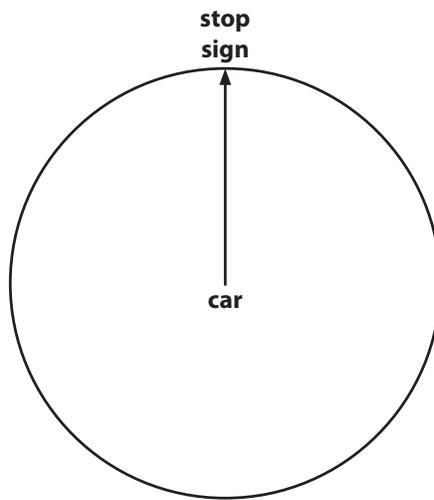


8. Imagine you are standing at the **house** and facing the **flower**.
Point to the **stop sign**.



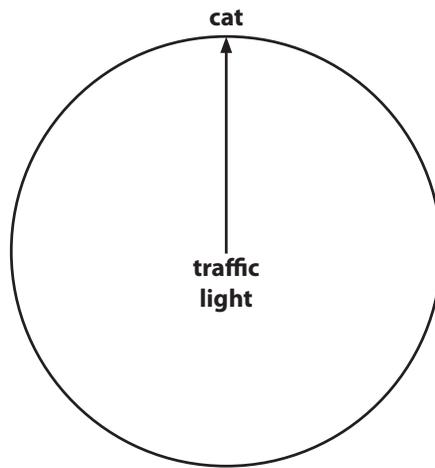


9. Imagine you are standing at the **car** and facing the **stop sign**.
Point to the **tree**.



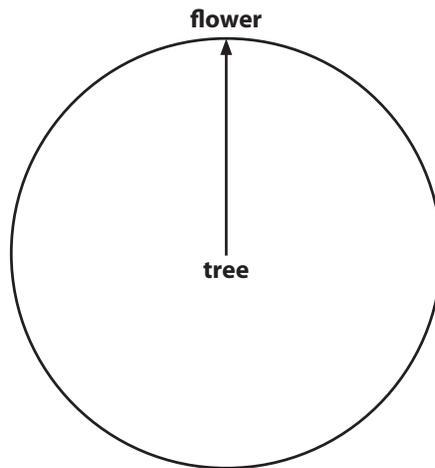


10. Imagine you are standing at the **traffic light** and facing the **cat**.
Point to the **car**.



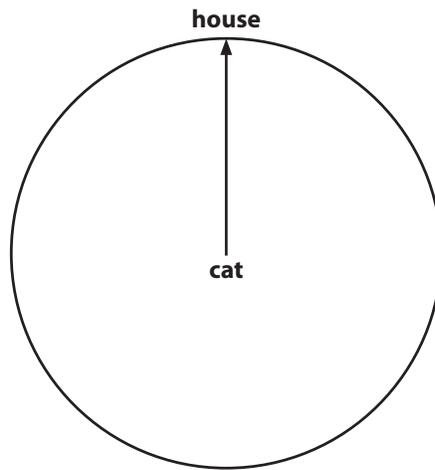


11. Imagine you are standing at the **tree** and facing the **flower**.
Point to the **house**.





12. Imagine you are standing at the **cat** and facing the **house**.
Point to the **traffic light**.



A.4 Questionnaire: Post-Experiment

A.4.1 Subjective Ratings

Subject# _____

B. The following questions are about your experience in Maze. Please ask the experimenter if you don't understand any question.

B0. How did you feel about your movement during virtual maze navigation/exploration? Is it close to any action you experience in the real world, such as driving, walking, skiing, swimming, climbing, or anything else? Please answer and explain why you felt in that way.

B1. Overall, how simple or complex is the maze designed for you to achieve the goal(s)?

Very simple 1-----2-----3-----4-----5-----6-----7 *Very complex*

B2. How easy or difficult have you found it to finish route replication task?

Very easy 1-----2-----3-----4-----5-----6-----7 *Very difficult*

B3. How easy or difficult have you found it to traverse the maze using the given equipment (please do not count glasses)?

Very easy 1-----2-----3-----4-----5-----6-----7 *Very difficult*

B4. Did you get familiar with the virtual maze after you finished all the tasks? Please circle one:

No at all 1-----2-----3-----4-----5-----6-----7 *Completely*

B4-1. What do/does **help** you get familiar with the maze? (please mark one or multiple item(s))

Enough time

Enough repetitions

Others: _____

B4-2. What do/does **not help** you get familiar with the maze? (please mark one or multiple item(s))

Lack of time

Lack of repetitions

Others: _____

Subject# _____

B5. How much did the missing wall (or virtual black wall) affect your task performance?

Not at all 1-----2-----3-----4-----5-----6-----7 *Completely*

B6. What is/are your primary strategy/strategies to remember the route and to figure out the structure of the maze?

- ____ Remembering (e.g., the local structure of the maze, location of landmarks, right or left turns, others _____)
- ____ Thinking aloud (by talking to myself)
- ____ Counting (e.g., # of turns, # of steps/strides, # of waypoints, others _____.)
- ____ Estimation (e.g., time duration of movement, distance, others _____.)
- ____ Use of the starting point as a reference point
- ____ Muscle memory of the movement pattern using my body parts (e.g., fingers, legs)
- ____ Others (please explain more specific): _____

B6-1. How much did the given interface support you to use your strategy/-ies?

Not at all 1-----2-----3-----4-----5-----6-----7 *Completely*

Please explain how it helped you: _____

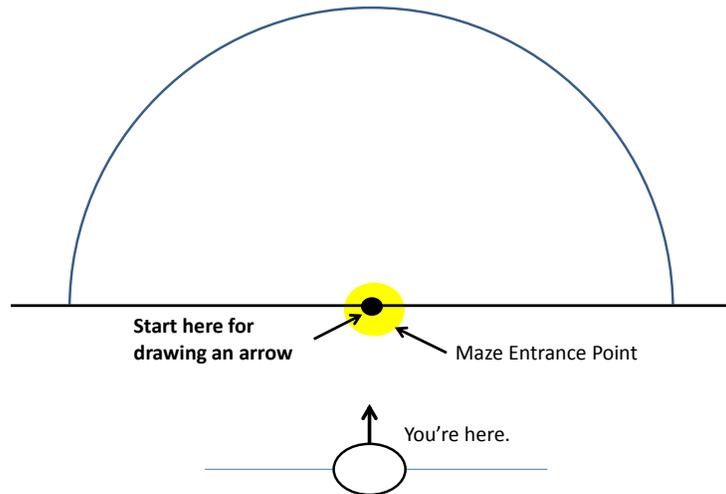
A.4.2 Direction Estimates to Landmarks

Subject# _____

B7. In the space provided below while facing the entrance point at your starting position, please draw two arrows from "Maze Entrance Point" to two landmarks (objects you met during maze navigation) of each path route and label each arrow.

B7-1. Red Path Route

Please name or describe two landmarks,
1st: _____, 2nd: _____
(If you don't remember, please ask the experimenter.)



B7-1-a. Please indicate your confidence level to indicate the direction to the 1st landmark. Please circle the number.

0----- 10 ----- 20 ----- 30 ----- 40 ----- 50 ----- 60 ----- 70 ----- 80 ----- 90 ----- 100 (%)

B7-1-b. Please indicate your confidence level to indicate the direction to the 2nd landmark. Please circle the number.

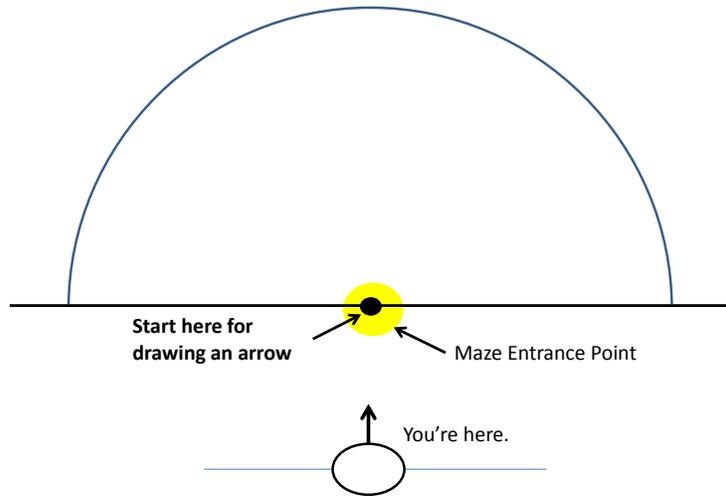
0----- 10 ----- 20 ----- 30 ----- 40 ----- 50 ----- 60 ----- 70 ----- 80 ----- 90 ----- 100 (%)

Subject# _____

B7-2. Blue Path Route

Please name or describe two landmarks,

1st : _____, 2nd : _____
(If you don't remember, please ask the experimenter.)



B7-2-a. Please indicate your confidence level to indicate the direction to the 1st landmark. Please circle the number.

0----- 10 ----- 20 ----- 30 ----- 40 ----- 50 ----- 60 ----- 70 ----- 80 ----- 90 ----- 100 (%)

B7-2-b. Please indicate your confidence level to indicate the direction to the 2nd landmark. Please circle the number.

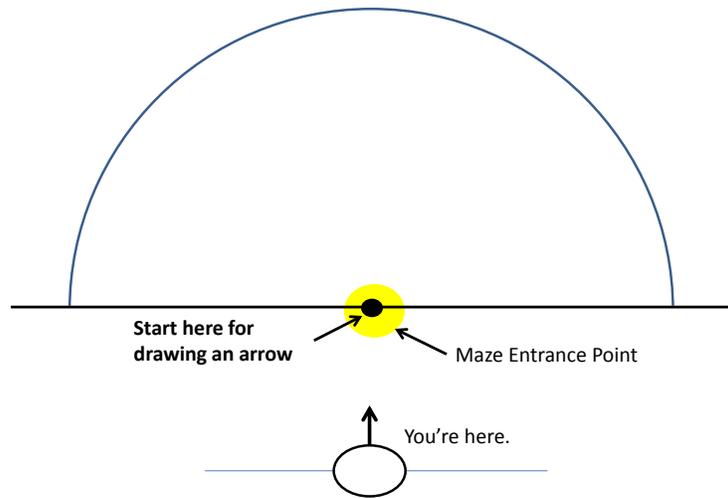
0----- 10 ----- 20 ----- 30 ----- 40 ----- 50 ----- 60 ----- 70 ----- 80 ----- 90 ----- 100 (%)

Subject# _____

B7-3. Yellow Path Route

Please name or describe two landmarks,

1st : _____, 2nd : _____
(If you don't remember, please ask the experimenter.)



B7-3-a. Please indicate your confidence level to indicate the direction to the 1st landmark. Please circle the number.

0----- 10 ----- 20 ----- 30 ----- 40 ----- 50 ----- 60 ----- 70 ----- 80 ----- 90 ----- 100 (%)

B7-3-b. Please indicate your confidence level to indicate the direction to the 2nd landmark. Please circle the number.

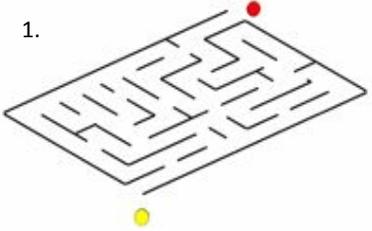
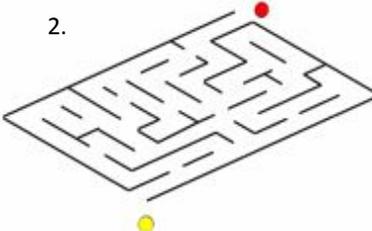
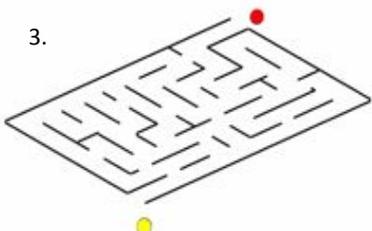
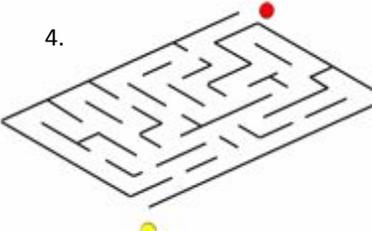
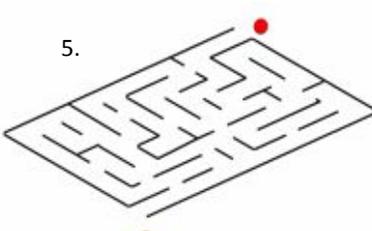
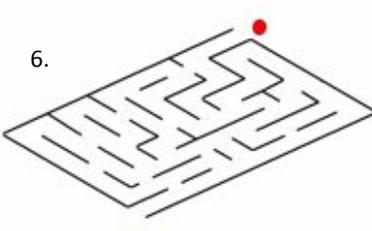
0----- 10 ----- 20 ----- 30 ----- 40 ----- 50 ----- 60 ----- 70 ----- 80 ----- 90 ----- 100 (%)

STOP HERE AND CALL THE EXPERIMENT ADMINISTRATOR

A.4.3 Selection of Correct Maze: Survey Knowledge

Subject# _____

B8. Please circle the maze number to indicate which one of the mazes shown below is the one you just traveled. (**Completion Time:** _____)

1. 	2. 
3. 	4. 
5. 	6. 

B8-a. Please indicate your confidence level of your answer to the question above.

0----- 10 ----- 20 ----- 30 ----- 40 ----- 50 ----- 60 ----- 70 ----- 80 ----- 90 ----- 100 (%)

A.4.4 Presence Questionnaire

Subject# _____

P. The following questions are about the experienced environment.

Characterize your experience in the environment, by marking an “X” in the appropriate box of the 7-point scale, in accordance with the question content and descriptive labels. Please consider the entire scale when making your responses, as the intermediate levels may apply. Answer the questions independently in the order that they appear. Do not skip questions or return to a previous question to change your answer.

P1. How much were you able to control events?

Not at all			Somewhat			Completely

P2. How natural did your interactions with the environment seem?

Extremely artificial			Borderline			Completely natural

P3. How much did the visual aspects of the environment involve you?

Not at all			Somewhat			Completely

P4. How natural was the mechanism which controlled movement through the environment?

Extremely artificial			Borderline			Completely natural

P5. How much did your experiences in the virtual environment seem consistent with your real world experiences?

Not consistent			Moderately consistent			Very consistent

P6. Were you able to anticipate what would happen next in response to the actions that you performed?

Not at all			Somewhat			Completely

A.4.5 Subjective Concentration on Tasks

Subject# _____

Q. Somehow, you might not fully pay attention to the experiment tasks including what you were told from the experiment. How much did you pay attention to each task?

Q-1 Memorizing the route while you were following red marker objects
Not at all 1-----2-----3-----4-----5-----6-----7 **Completely**

Q-2 Memorizing the route while you were following blue marker objects
Not at all 1-----2-----3-----4-----5-----6-----7 **Completely**

Q-3 Memorizing the route while you were following yellow marker objects
Not at all 1-----2-----3-----4-----5-----6-----7 **Completely**

Q-4 Building the structure of the maze while you were freely navigating
Not at all 1-----2-----3-----4-----5-----6-----7 **Completely**

Any comment?

-

-

-

-

-

-

-

-

-

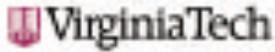
-

Thank you!

Appendix B

Experiment Documents for Exploration Study on Perception

B.1 Approval Letter from IRB at Virginia Tech



Office of Research Compliance
 Institutional Review Board
 2000 Kraft Drive, Suite 2000 (0497)
 Blacksburg, VA 24060
 540/231-4606 Fax 540/231-0959
 email irb@vt.edu
 website <http://www.irb.vt.edu>

MEMORANDUM

DATE: October 22, 2012
TO: Denis Gracanin, Ji Sun Kim, Francis Quek
FROM: Virginia Tech Institutional Review Board (FWA00000572, expires May 31, 2014)
PROTOCOL TITLE: Exploration of Human Spatial Perception in 3D Immersive Virtual Environments
IRB NUMBER: 12-683

Effective October 22, 2012, the Virginia Tech Institutional Review Board (IRB) Chair, David M Moore, approved the Amendment request for the above-mentioned research protocol.

This approval provides permission to begin the human subject activities outlined in the IRB-approved protocol and supporting documents.

Plans to deviate from the approved protocol and/or supporting documents must be submitted to the IRB as an amendment request and approved by the IRB prior to the implementation of any changes, regardless of how minor, except where necessary to eliminate apparent immediate hazards to the subjects. Report within 5 business days to the IRB any injuries or other unanticipated or adverse events involving risks or harms to human research subjects or others.

All investigators (listed above) are required to comply with the researcher requirements outlined at:

<http://www.irb.vt.edu/pages/responsibilities.htm>

(Please review responsibilities before the commencement of your research.)

PROTOCOL INFORMATION:

Approved As: **Expedited, under 45 CFR 46.110 category(ies) 6,7**
 Protocol Approval Date: **August 15, 2012**
 Protocol Expiration Date: **August 14, 2013**
 Continuing Review Due Date*: **July 31, 2013**

*Date a Continuing Review application is due to the IRB office if human subject activities covered under this protocol, including data analysis, are to continue beyond the Protocol Expiration Date.

FEDERALLY FUNDED RESEARCH REQUIREMENTS:

Per federal regulations, 45 CFR 46.103(f), the IRB is required to compare all federally funded grant proposals/work statements to the IRB protocol(s) which cover the human research activities included in the proposal / work statement before funds are released. Note that this requirement does not apply to Exempt and Interim IRB protocols, or grants for which VT is not the primary awardee.

The table on the following page indicates whether grant proposals are related to this IRB protocol, and which of the listed proposals, if any, have been compared to this IRB protocol, if required.

Invest the Future

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY
 AN EQUAL OPPORTUNITY AFFIRMATIVE ACTION INSTITUTION

Date*	OSP Number	Sponsor	Grant Comparison Conducted?

* Date this proposal number was compared, assessed as not requiring comparison, or comparison information was revised.

If this IRB protocol is to cover any other grant proposals, please contact the IRB office (irbadmin@vt.edu) immediately.

B.2 Approved Informed Consent from IRB at Virginia Tech

Informed Consent for Participant of Investigative Project Virginia Polytechnic Institute and State University

Title of Project: **Exploration of Human Spatial Perception in 3D Immersive Virtual Environments**

Principal Investigator: Dr. Denis Gracanin

I. THE PURPOSE OF THIS RESEARCH/PROJECT

You are invited to participate in a study of interaction in a 3D immersive virtual environment (named CAVE or VisCube). This research studies the ways people act and work in a 3D virtual world. This study involves experimentation for the purpose of evaluating and improving the user interface and observing user behaviors in virtual environments.

II. PROCEDURES

You will be asked to fill out pre-experiment questionnaire with regard to your background and spatial ability.

You will be asked to perform a set of tasks using a virtual environment system, including practice tasks. These tasks include exploring several virtual objects and accurately perceive the spatial aspects, e.g., size, shape and distance between two objects, of the objects. In order to complete the tasks, you must be able to distinguish different colors of the objects. You will use one interface to perform a set of tasks in the VisCube (i.e., CAVE™) system. We are **not evaluating you or your performance in any way**; you are helping us to evaluate our system. The time you take to do each task and other aspects of your interaction with the system will be measured. You may be asked questions during and after the evaluation, in order to clarify our understanding of your evaluation.

You will also be asked to fill out post-experiment questionnaire after you finish the experiment tasks.

The session will last approximately 100 minutes in total including short breaks. The tasks are not tiring but need your attention. You are welcome to take a break as needed. You may also terminate your participation at any time for any reason.

You will be given full instructions before every task. Because we are measuring a range of abilities, some tasks will be easy and others difficult. It is important that you understand the instructions before beginning each task. If anything is unclear, be sure to ask us questions.

III. RISKS

The proposed experiments are straightforward tests using our hands, fingers, or other body parts in virtual environments. Participation involves standing on a semi-enclosed platform with three walls on the floor and performing experiment tasks. The physical components of these tasks are not stressful. The only foreseeable physical risks are slight eye and leg strain, headache, dizziness, or mild nausea. There are no known mental risks.

If you experience any eye or leg strain, headache, dizziness, or nausea during the session, then please tell the investigator and step away from the floor and take a break. The investigator will explain when you can take such breaks. If you are having trouble with any task, please tell us. If dizziness or nausea becomes uncomfortable, you will be allowed to leave.

IV. BENEFITS OF THIS PROJECT

Your participation in this study will provide information that may be used to improve the interface design of virtual environments hardware and/or software. No guarantee of benefits has been made to encourage you to participate. You may receive a synopsis summarizing this research when completed if you want.

You are requested to refrain from discussing the evaluation with other people who might be in the candidate pool from which other participants might be drawn.

V. EXTENT OF ANONYMITY AND CONFIDENTIALITY

The results of this study will be kept strictly confidential. Your written consent is required for the researchers to release any data identified with you as an individual to anyone other than personnel working on the project. The information you provide will have your name removed and only a subject number will identify you during analyses and any written reports of the research.

The experiment may be taken by a camera. We are interested in observing participants' behaviors. We avoid taking a video of participants' faces. If it is taken, the films (or files from a digital camera) will be stored securely, viewed only by the experimenters (Denis Gracanin and Ji-Sun Kim) and erased after those are stored in a secured hard drive. If the experimenters wish to use a portion of your picture for any other purpose, they will get your written permission before using it. Your signature on this form does not give them permission to show your picture to anyone else.

VI. COMPENSATION

1. For the participants from the SONA system at Department of Psychology;
If you quit during the experiment regardless of reason, you will get partial credit(s). Otherwise you will get full credit(s) as the SONA system provides.
2. For the participants from mailing lists;
Your participation is voluntary and unpaid.

VII. FREEDOM TO WITHDRAW

You are free to withdraw from this study at any time for any reason.

VIII. SUBJECT'S RESPONSIBILITIES AND PERMISSION

I voluntarily agree to participate in this study, and I know of no reason I cannot participate. I have read and understand the informed consent and conditions of this project. I have had all my questions answered. I hereby acknowledge the above and give my voluntary consent for participation in this project. If I participate, I may withdraw at any time without penalty. I agree to abide by the rules of this project

Signature

Date

Name (please print)

Contact: phone or address or
email address (OPTIONAL)

Should I have any questions about this research or its conduct, I may contact:

- Chair: Dr. David Moore
IRB Chair Phone (540) 231-4991
Email: moored@vt.edu
- Investigator: Dr. Denis Gracanin Phone (540)231-2060
Associate Professor of Computer Science
Email: gracanin@vt.edu
- Dr. Francis Quek Phone (540)
Professor of Computer Science
Email: quek@vt.edu
- Ji-Sun Kim (hideaway@vt.edu)
Ph.D. Candidate of Computer Science
- Cc: the participant, Dr. Denis Gracanin

B.3 Questionnaire: Pre-Experiment

B.3.1 Background

Subject# _____

Exploration of Human Spatial Perception in 3D Immersive Virtual Environments

A. The following questions are about your general background.

A1. Age: _____

A2. Please circle your gender: Female Male

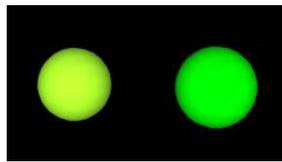
A3. Occupation (if student, indicate graduate or undergraduate): _____
Major / Area of specialization: _____

A4. Do you wear prescription glasses or corrective contact lenses? __ Yes / __ No

A4-(a) If yes, are you wearing them now? __ Yes / __ No

A4-(b) If you answer "No" in A4-(a), but you need to wear glasses or contact lenses but you are not wearing them now, can you see detail of distant objects (3 – 7 feet or 1 -2 meters away from you)? __ Yes / __ No

A5. Please answer if two balls below have the same color or different colors.



___ Same color/ ___ Different colors

A5-1. In general, do you have any problem to distinguish different colors? __ Yes / __ No

IF YES, PLEASE STOP HERE AND CALL THE EXPERIMENT ADMINSTRATOR

A6. Please rate your experience level with Immersive Virtual Reality Systems

No experience 1-----2-----3-----4-----5-----6-----7 Expert

A6-1. If your rate is greater than 1, please circle or write what you experienced: CAVE, HMD, Others: _____

PLEASE CONTINUE ON THE BACKSIDE OF THIS PAGE

Subject# _____

A7. Please rate your experience level with 3D modeling tools (e.g., CAD, Blender, 3DS-MAX, etc.)

No experience 1-----2-----3-----4-----5-----6-----7 **Expert**

A8. Please rate your experience level with a joystick input device (any type) to navigate any 3D virtual/computer space (e.g., 3D games)

No experience 1-----2-----3-----4-----5-----6-----7 **Expert**

A9. Please rate your experience level with a touch-based input device (any type, e.g., smartphone, tablet pad, etc.) to navigate any 3D virtual/computer space (e.g., 3D games).

No experience 1-----2-----3-----4-----5-----6-----7 **Expert**

A10. Have you experienced 3D virtual navigation/exploration with any other input device except for Joystick or Touch-based input device? ___ **Yes** / ___ **No**

If yes, please list the input device names: _____

A11. Rate your current tiredness level, including nausea, dizziness, and headache.

Very tired 1-----2-----3-----4-----5-----6-----7 **Not tired at all**

STOP HERE AND CALL THE EXPERIMENT ADMINISTRATOR

B.3.2 Spatial Ability Test: Cube Comparison

Name _____

CUBE COMPARISONS TEST -- S-2 (Rev.)

Wooden blocks such as children play with are often cubical with a different letter, number, or symbol on each of the six faces (top, bottom, four sides). Each problem in this test consists of drawings of pairs of cubes or blocks of this kind. Remember, there is a different design, number, or letter on each face of a given cube or block. Compare the two cubes in each pair below.

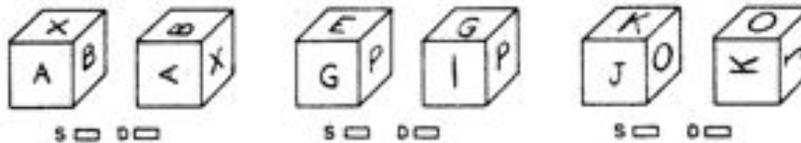


The first pair is marked D because they must be drawings of different cubes. If the left cube is turned so that the A is upright and facing you, the N would be to the left of the A and hidden, not to the right of the A as is shown on the right hand member of the pair. Thus, the drawings must be of different cubes.

The second pair is marked S because they could be drawings of the same cube. That is, if the A is turned on its side the X becomes hidden, the B is now on top, and the C (which was hidden) now appears. Thus the two drawings could be of the same cube.

Note: No letters, numbers, or symbols appear on more than one face of a given cube. Except for that, any letter, number or symbol can be on the hidden faces of a cube.

Work the three examples below.



The first pair immediately above should be marked D because the X cannot be at the peak of the A on the left hand drawing and at the base of the A on the right hand drawing. The second pair is "different" because P has its side next to G on the left hand cube but its top next to G on the right hand cube. The blocks in the third pair are the same, the J and K are just turned on their side, moving the O to the top.

Your score on this test will be the number marked correctly minus the number marked incorrectly. Therefore, it will not be to your advantage to guess unless you have some idea which choice is correct. Work as quickly as you can without sacrificing accuracy.

You will have 3 minutes for each of the two parts of this test. Each part has one page. When you have finished Part 1, STOP.

DO NOT TURN THE PAGE UNTIL YOU ARE ASKED TO DO SO.

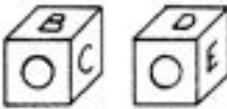
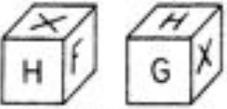
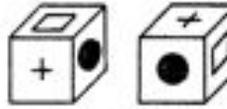
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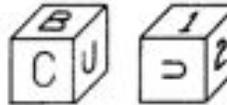
Part 1 (3 minutes)

1. 2. 3. 4. 5. 6. 7. 8. 9. 10. 11. 12. 13. 14. 15. 16. 17. 18. 19. 20. 21.

DO NOT GO ON TO THE NEXT PAGE UNTIL ASKED TO DO SO. STOP.

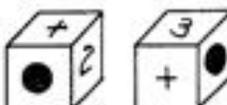
Part 2 (5 minutes)

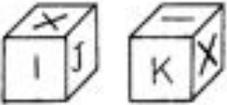
22.  23.  24. 

25.  26.  27. 

28.  29.  30. 

31.  32.  33. 

34.  35.  36. 

37.  38.  39. 

40.  41.  42. 

DO NOT GO BACK TO PART 1 AND
DO NOT GO ON TO ANY OTHER TEST UNTIL ASKED TO DO SO. STOP.

B.3.3 Experimenter Notes for Experiment

Subject# _____

B. Size Perception Task.

Find which object is identical to the object in the glass box as indicated in each question. (Maximum allocated time is 1.5 min. per task)

B1. Box #2. The user's answer: ____ (Taken Time: _____)

Confidence Level:

0----- 10 ----- 20 ----- 30 ----- 40 ----- 50 ----- 60 ----- 70 ----- 80 ----- 90 ----- 100 (%)

B2. Box #3. The user's answer: ____ (Taken Time: _____)

Confidence Level:

0----- 10 ----- 20 ----- 30 ----- 40 ----- 50 ----- 60 ----- 70 ----- 80 ----- 90 ----- 100 (%)

B3. Box #1. The user's answer: ____ (Taken Time: _____)

Confidence Level:

0----- 10 ----- 20 ----- 30 ----- 40 ----- 50 ----- 60 ----- 70 ----- 80 ----- 90 ----- 100 (%)

B4. Box #2. The user's answer: ____ (Taken Time: _____)

Confidence Level:

0----- 10 ----- 20 ----- 30 ----- 40 ----- 50 ----- 60 ----- 70 ----- 80 ----- 90 ----- 100 (%)

B5. Box #1. The user's answer: ____ (Taken Time: _____)

Confidence Level:

0----- 10 ----- 20 ----- 30 ----- 40 ----- 50 ----- 60 ----- 70 ----- 80 ----- 90 ----- 100 (%)

B6. Box #2. The user's answer: ____ (Taken Time: _____)

Confidence Level:

0----- 10 ----- 20 ----- 30 ----- 40 ----- 50 ----- 60 ----- 70 ----- 80 ----- 90 ----- 100 (%)

B7. Box #3. The user's answer: ____ (Taken Time: _____)

Confidence Level:

0----- 10 ----- 20 ----- 30 ----- 40 ----- 50 ----- 60 ----- 70 ----- 80 ----- 90 ----- 100 (%)

B8. Box #1. The user's answer: ____ (Taken Time: _____)

Confidence Level:

0----- 10 ----- 20 ----- 30 ----- 40 ----- 50 ----- 60 ----- 70 ----- 80 ----- 90 ----- 100 (%)

Subject# _____

C. Shape Perception Task.

Find which object is identical to the object in the glass box as indicated in each question. (Maximum allocated time is 1.5 min. per task)

C1. Box #3. The user's answer: ____ (Taken Time: _____)

Confidence Level:

0----- 10 ----- 20 ----- 30 ----- 40 ----- 50 ----- 60 ----- 70 ----- 80 ----- 90 ----- 100 (%)

C2. Box #1. The user's answer: ____ (Taken Time: _____)

Confidence Level:

0----- 10 ----- 20 ----- 30 ----- 40 ----- 50 ----- 60 ----- 70 ----- 80 ----- 90 ----- 100 (%)

C3. Box #1. The user's answer: ____ (Taken Time: _____)

Confidence Level:

0----- 10 ----- 20 ----- 30 ----- 40 ----- 50 ----- 60 ----- 70 ----- 80 ----- 90 ----- 100 (%)

C4. Box #3. The user's answer: ____ (Taken Time: _____)

Confidence Level:

0----- 10 ----- 20 ----- 30 ----- 40 ----- 50 ----- 60 ----- 70 ----- 80 ----- 90 ----- 100 (%)

C5. Box #1. The user's answer: ____ (Taken Time: _____)

Confidence Level:

0----- 10 ----- 20 ----- 30 ----- 40 ----- 50 ----- 60 ----- 70 ----- 80 ----- 90 ----- 100 (%)

C6. Box #2. The user's answer: ____ (Taken Time: _____)

Confidence Level:

0----- 10 ----- 20 ----- 30 ----- 40 ----- 50 ----- 60 ----- 70 ----- 80 ----- 90 ----- 100 (%)

C7. Box #1. The user's answer: ____ (Taken Time: _____)

Confidence Level:

0----- 10 ----- 20 ----- 30 ----- 40 ----- 50 ----- 60 ----- 70 ----- 80 ----- 90 ----- 100 (%)

C8. Box #3. The user's answer: ____ (Taken Time: _____)

Confidence Level:

0----- 10 ----- 20 ----- 30 ----- 40 ----- 50 ----- 60 ----- 70 ----- 80 ----- 90 ----- 100 (%)

Subject# _____

D. Distance Perception Task.

Find which object has the same distance between two components (indicated by a different color) of that of the object in the glass box as indicated in each question. (Maximum allocated time is 1.5 min. per task)

D1. Box #3. The user's answer: ____ (Taken Time: _____)

Confidence Level:

0----- 10 ----- 20 ----- 30 ----- 40 ----- 50 ----- 60 ----- 70 ----- 80 ----- 90 ----- 100 (%)

D2. Box #3. The user's answer: ____ (Taken Time: _____)

Confidence Level:

0----- 10 ----- 20 ----- 30 ----- 40 ----- 50 ----- 60 ----- 70 ----- 80 ----- 90 ----- 100 (%)

D3. Box #3. The user's answer: ____ (Taken Time: _____)

Confidence Level:

0----- 10 ----- 20 ----- 30 ----- 40 ----- 50 ----- 60 ----- 70 ----- 80 ----- 90 ----- 100 (%)

D4. Box #2. The user's answer: ____ (Taken Time: _____)

Confidence Level:

0----- 10 ----- 20 ----- 30 ----- 40 ----- 50 ----- 60 ----- 70 ----- 80 ----- 90 ----- 100 (%)

D5. Box #2. The user's answer: ____ (Taken Time: _____)

Confidence Level:

0----- 10 ----- 20 ----- 30 ----- 40 ----- 50 ----- 60 ----- 70 ----- 80 ----- 90 ----- 100 (%)

D6. Box #3. The user's answer: ____ (Taken Time: _____)

Confidence Level:

0----- 10 ----- 20 ----- 30 ----- 40 ----- 50 ----- 60 ----- 70 ----- 80 ----- 90 ----- 100 (%)

D7. Box #1. The user's answer: ____ (Taken Time: _____)

Confidence Level:

0----- 10 ----- 20 ----- 30 ----- 40 ----- 50 ----- 60 ----- 70 ----- 80 ----- 90 ----- 100 (%)

D8. Box #2. The user's answer: ____ (Taken Time: _____)

Confidence Level:

0----- 10 ----- 20 ----- 30 ----- 40 ----- 50 ----- 60 ----- 70 ----- 80 ----- 90 ----- 100 (%)

B.4 Questionnaire: Post-Experiment

B.4.1 Subjective Ratings

Subject# _____

E. The following questions are about your overall experience of the given interface (Please do not take into account any practice task when answering the questions.)

E1. Please rate the level of difficulty/effectiveness of using the given interface to complete the given tasks.

Very Difficult 1-----2-----3-----4-----5-----6-----7 **Very Effective**

Please comment: _____

E2. Please rate the speed of movement of using the given interface to move around the given objects.

Uncomfortable 1-----2-----3-----4-----5-----6-----7 **Comfortable**

Please comment: _____

E3. Rate your current tiredness level, including nausea, dizziness, and headache.

Very tired 1-----2-----3-----4-----5-----6-----7 **Not tired at all**

Any other comment?

Thank you!